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THE ASTROPHYSICAL JOURNAL

NUMBER 5

AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE

Mount Wilson Solar Observatory of the
Carnegie Institution of Washington

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University of Chicago

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JUNE 1918

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ON THE CORRECTION OF OPTICAL SURFACES

By A. A. MICHELSON

In a recent number of the *Philosophical Magazine* (6), 35, 49, 1918, an interesting method for correcting optical surfaces by means of the interferometer was developed by F. Twyman. While nothing in the paper indicates that the method is limited to relatively small surfaces, it would appear that such an application to mirrors and lenses of the size of modern astronomical telescopes can hardly be contemplated, as it would involve interferometers of at least equal dimensions.

It was hoped that the modification of Twyman's method represented in Fig. 1 might avoid this difficulty. S is the light-source at the focus of a collimating lens A . Thence the light passes to the dividing surface O , part passing through the achromatic lens B and forming an image of S at the focus of the lens L to be tested. The light returns from the plane mirror M and interferes with the light reflected from O to P and back.

It appears, however, that unless the two optical paths OM and OP are equal—which would involve the presence of a second large lens similar to L —the (circular) interference bands are extremely small and difficult to observe. Even though this difficulty were overcome the assistance of an optically perfect lens B is indispensable.

In view of these difficulties the following simple scheme was put into operation and found entirely satisfactory (Fig. 2). The light from a Nernst glower is concentrated on the slit *S* by means of a

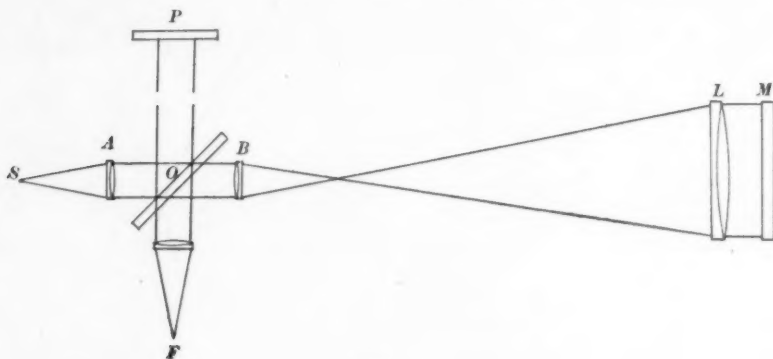


FIG. 1

microscope objective *O*, whence by a total reflection prism it is reflected to a concave mirror 6 inches in diameter and of 36 inches radius.¹ The image of the slit is formed immediately above the

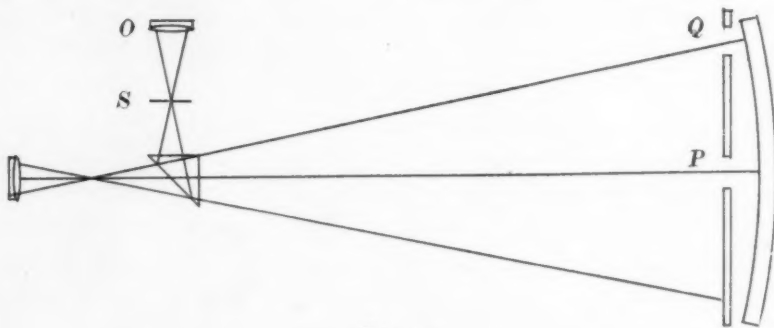


FIG. 2

prism and is viewed by a microscope with a $\frac{1}{12}$ -inch objective. A series of screens with two rectangular apertures² *Q* and *P* are placed immediately in front of the mirror, one aperture at the center and

¹ This was a mirror in process of polishing and was purposely selected on account of its relatively large errors.

² The series of screens could advantageously be replaced by a double-slit mechanism which permits of a continuous variation of the distance *PQ*.

the other at varying distances, producing interference bands, the central band corresponding exactly with the position of the slit image if the mirror is perfect. The distance between the centers of band and the slit image in fractions of the fringe-width gives twice the error of the mirror at the point of the mirror corresponding to the position of the aperture Q in light-waves.

These errors are determined for points Q distant from the center P by 2, 3, 4, 5, 6, and 7 cm. A second set of measurements is taken with Q at the opposite end of the diameter.

Such double sets are repeated at intervals of 45° rotation of the mirror about its axis, through 360° , and the results plotted as represented in Fig. 3. The numbers represent hundredths of a fringe. A second trial gave results differing, on the average, from the first by less than 0.02 fringe or 0.01 of a light-wave.

A similar investigation of a 5-inch achromatic lens by O. L. Petitdidier,¹ $f=12$ ft., backed by a plane mirror¹ used for spectrographic work, showed errors so small that artificial errors were introduced by placing in the path of the pencil a plane-parallel plate 2 inches in diameter, which had been made roughly cylindrical by retouching, at 4 feet from the focus.

The resulting errors are plotted in Fig. 4. The plane-parallel plate was then corrected by local retouching, and the corresponding errors are given in Fig. 5.

Fig. 6 shows a series of photographs of the slit image before correction (under a magnification of about 1000 diameters) at intervals of 45° rotation of the lens and shows clearly the effects of the astigmatism.

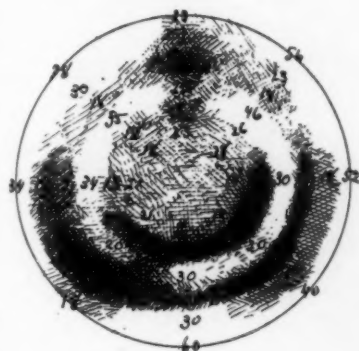


FIG. 3.—6-inch mirror. Radius 35 inches. Mean error 0.19 fringes.

¹ On account of the secondary chromatic aberration the light used was approximately homogeneous, corresponding in wave-length with the yellow Hg line.

Fig. 7 gives the corresponding photographs of the slit image after correction. The result is a practically perfect image. It may be added that the entire process of investigation of errors and succeeding corrections took about six hours.

It is clear that such a process of correction may be applied to even the largest astronomical mirrors or lenses, both as an assistance in the original figuring¹ and in the final correction, and that such final corrections may be made without risk of injury to the objective by an auxiliary correcting plate placed anywhere between the objective and focus.²

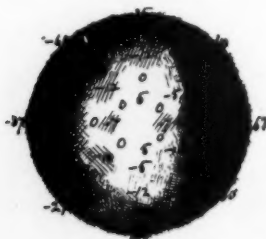


FIG. 4.—Before correcting, mean error 0.29 fringes.



FIG. 5.—After correcting, mean error 0.04 fringes

There is one very important precaution to be observed in these measurements—especially for lenses or mirrors of large aperture: great care must be exercised in the focal adjustment. If, for instance, h is the depth of a concave mirror under observation, r the radius of its disk, and R the radius of curvature, $h = \frac{r^2}{2R}$ and $\delta h = \frac{r^2}{2R^2} \delta R$. Thus if, as in the foregoing investigation, $\frac{r}{R} = \frac{1}{6}$, $\delta R = 72 \delta h$. If then δh is to be correct to within 0.1λ , δR must not exceed 7.2λ or 0.0036 mm.

A similar remark applies (though in less degree) to the selection and maintenance of the wave-length of the light employed if the objective be an achromatic lens.

Paraboloidal or ellipsoidal surfaces as well as spherical.

² If, however, the errors are confined to relatively small areas, the correcting plate must be near the objective.

PLATE VI

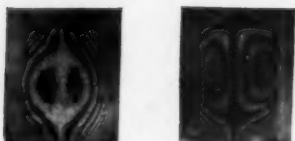
FIG. 6



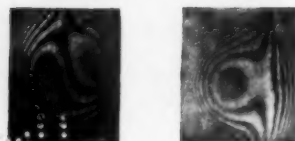
FIG. 7



c, d



e, f



a



b

FIG. 10

f

FIG. 11

THE CORRECTION OF OPTICAL SURFACES
(*f* corresponds with *a*; *e* with *b*)

With evident modifications the same method applies to the correction of prisms and gratings. Here of course the order of accuracy attainable depends on the degree of homogeneity of the light-source. A cadmium lamp is amply sufficient for anything below a required resolving power of, say, 500,000, but this may not furnish sufficient light to observe the interference fringes under the high magnification required, especially as the cadmium lines broaden considerably as the luminosity increases.

A quartz mercury lamp has been found to be fairly effective.

Evidently the interferometer method, as shown in Fig. 8, or even more simply a single plane-parallel plate, Fig. 9, may be

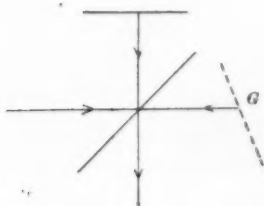


FIG. 8

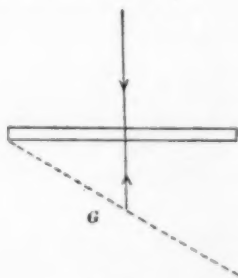


FIG. 9

applied. In either case, with proper adjustment, the interference fringes are concentric circles, and if the grating *G* (and of course the auxiliary surfaces) be perfect, the diameter of these circular fringes remains constant when the eye or the observing telescope is moved about in any direction. The errors may thus be determined and the auxiliary plate may be corrected at the corresponding points.¹

In the method of Fig. 9 there is no singularity to be met, such as occurs in the shape of the interference fringes in the method of Fig. 8 in the vicinity of zero difference in path. These singular figures are shown in the photographs² (Fig. 10) for various adjustments of the angles of the mirror.

¹ This would be good for only one order of spectrum, though by rotating the correcting plate in the same sense as the grating there would still be partial compensation.

² It should be noted that these photographs are taken with a small diaphragm. If the entire aperture is used (focused for parallel rays), the entire interference system reduces to the single circular fringe.

The difference in path of the two interfering pencils is given by

$$\Delta = \frac{2c}{S^2}(y - y_0)(x^2 + y^2) + ax + \beta y$$

in which c is the tangent of the angle which the grating makes with the wave-front;

S = distance of the eye from the mirror;

a = "error" of adjustment in altitude;

β = "error" of adjustment in azimuth.

(Grating rulings vertical.)

Fig. 11 gives two cases which have been calculated for $\Delta = 1, 2, 3$, etc. 11a for $a = 0, \beta = -2, y_0 = 1$, and 11b for $a = 0.1, \beta = -2, y_0 = 0$.

RYERSON PHYSICAL LABORATORY

UNIVERSITY OF CHICAGO

May 1918

ON THE CAUSE UNDERLYING THE SPECTRAL DIFFERENCES OF THE STARS

By C. D. PERRINE

Some recent investigations have led to an explanation of the strong affinity of the stars of Class B for the Milky Way and of a relation of the spectral differences in the components of double stars to their distance from the sun. Briefly it is that the spectral and perhaps other characteristics of these stars, in common with the novae, are due chiefly to conditions existing in the more distant regions of the galaxy instead of wholly to a process of development through radiation and condensation. This explanation was suggested largely by the fact that Nova Persei No. 2 (the only nova observed before the appearance of bright lines) passed through the B-type stage at or about the time of its greatest brightness.

Such a hypothesis involves the entire question of evolution, as it tends to make location in the system and external causes of equal or greater importance than the elements of time or mass in determining the physical conditions of the stars belonging to our system. It appears to have but little bearing on the ultimate life-history of the system as a whole, its beginning, or its end.

Further consideration and study have brought to light other facts which appear to bear also upon this question and which will be discussed in what follows from the broader standpoint of their relation to the processes of evolution.

Relation of the spectral differences in the components of double stars to distance as indicated by proper motion.—It seemed desirable to investigate what was believed to be contrary evidence afforded by the spectral differences of the components of double stars. It was seen almost at once that there was a relation between these spectral differences other than the well-known conclusion that in contrasted pairs the fainter component is generally of the earlier spectral type.¹

¹ Clerke, *Problems in Astrophysics*, p. 263.

It was found that this condition appears to be related to the size of the proper motions and therefore to the distance of the stars from the sun. Other investigators have noticed that a few of the fainter components of double stars give spectra of later type, but appear to have ascribed little or no importance to the contradiction, none so far as I know attempting other explanation than a purely accidental one.

The data used for this investigation are taken from the observations of the spectra of 745 double stars made at Harvard and classified by Miss Cannon.¹

For obvious reasons this preliminary investigation was limited to stars known either to be binary or to have common proper motion whose differences of brightness are approximately half a magnitude or greater. There were found 78 of such stars in that list.

It was first observed that the stars in which the fainter component was of the earlier type were in general closer together than those in which the companion was of a later type. Before being able to draw any conclusions it was desirable to get some idea of the effect of distance from the observer on the actual separations. This was investigated through the medium of the proper motions. The result has been almost as startling as it was unexpected in indicating that *the relative spectral types of the components depend upon their distances from the sun, those pairs in which the fainter component is of earlier type being distant, whereas those in which the fainter component is of later type are much nearer.* I have encountered few facts more significant than this appears to be. It is, in my opinion, difficult to exaggerate its importance in connection with the physical condition of the various bodies composing our stellar system. For this reason the data will be examined in considerable detail.

The stars selected as suitable from the Harvard results are given in the accompanying tables, together with the total proper motions of the systems as computed from data given in Boss's *Preliminary General Catalogue*.

Of these stars, 26 have the fainter components of later type, 28 have them of earlier type, and 24 are of the same type.

¹ *Harvard Annals*, 56, Pt. 7.

The stars were grouped according to whether the fainter component is of later spectral type than the primary (Table I), or whether it is of earlier type (Table II). Although undoubtedly of much interest and importance in detailed studies of the spectral

TABLE I
FAINTER COMPONENT OF LATER TYPE

STAR	1900.0		MAG. BRIGHTER COMPONENT	Δ MAG.	SPECTRAL CLASS		μ	s
	α	δ			Brighter	Fainter		
{ Piscium.....	1 ^h 8 ^m 5	+ 7° 3'	5.6	0.9	A5	G5	0.143	23.7
37 Ceti.....	1 9.4	- 8 28	5.2	2.6	F5	G	.295	49.4
γ Arietis.....	1 48.0	+18 49	4.8	4.8	Ap	K	.138	222.8
59 Andromedae	2 4.8	+38 34	6.0	0.7	A0	A2	.025	16.6
η Tauri.....	3 41.5	+23 48	3.0	3.3	B5	A0	.052	117.3
f Eridani.....	3 44.9	-37 55	4.9	0.6	B8	A0	.082	7.8
θ Tauri.....	4 22.9	+15 39	3.6	0.5	A5	K0	.107	337.1
α Leonis.....	10 3.0	+12 27	1.3	6.3	B8	G	.247	176.7
H.R. 4191.....	10 37.7	+46 44	5.3	1.8	F0	G0	.289	288.1
r7 Comae Ber	12 23.9	+26 28	5.4	1.4	Aop	A3	.029	145.3
α Centauri.....	14 32.8	-60 25	0.3	1.4	G0	K5	3.67	21.9
α Librae.....	14 45.3	-15 38	2.9	2.2	A2	F5	0.131	231.0
κ Lupi.....	15 5.0	-48 21	4.2	1.7	B9	A	.121	26.9
μ Boötis.....	15 20.7	+37 44	4.5	2.2	F0	K0	.169	108.3
ν Scorpii.....	16 6.2	-19 12	4.3	2.2	B3	A	.034	41.3
ϵ Normae.....	16 19.8	-47 20	4.8	2.7	B5	A	.010	22.8
b Draconis.....	18 22.5	+58 45	4.9	2.7	A2	F	.065	88.8
κ Coronae Aust.	18 26.5	-38 48	6.0	0.6	B8	A	.038	21.7
β Lyrae.....	18 46.4	+33 15	3.4*	4.4	B2	B3	.008	46.0
57 Aquilae.....	19 49.3	- 8 29	5.8	0.8	B3	A	.022	35.7
15 Cephei.....	22 0.6	+59 19	6.7	0.9	B0	B9	.013	183.4
15 Cephei.....	22 0.6	+59 19	6.8	0.8	B5	B9	.013	136.1
15 Cephei.....	22 0.6	+59 19	6.7	0.1	B0	B5	.013	236.3
15 Cephei.....	22 0.6	+59 19	6.8	1.0	B5	B9	.013	192.4
ξ Cephei.....	22 0.9	+64 8	4.6	1.9	A3	G?	.230	6.9
8 Lacertae.....*	22 31.4	+39 7	5.8	0.7	B3	B5	.018	22.4

* Var.

characteristics of double stars, including the present problem, those having both components alike in this respect will not be considered especially, although several peculiarities have been noticed.

An examination of the individual stars in Table I shows that all of those which have proper motions under 0".050, without exception, belong to Classes B and A. The differences of spectral class and of magnitude are also consistently smaller than for the stars having larger proper motions. This appears to be too consistent to be mere coincidence even in so small a number of stars, especially

in connection with the peculiarities of those stars whose components are of earlier types.

The consistency with which the 28 systems having their fainter components of earlier types show small proper motions is remarkable, especially when it is considered that all but four of these stars

TABLE II
FAINTER COMPONENT OF EARLIER TYPE

STAR	1900.0		MAG. BRIGHTER COMPONENT	Δ MAG.	SPECTRAL CLASS		μ	s
	α	δ			Brighter	Fainter		
ϵ Arietis.	1 ^h 44 ^m 6	+21°47'	6.2	1.2	G0	A	0".018	2.9
α Piscium.	1 56.9	+ 2 17	4.3	0.9	A3	A	.042	2.6
γ Andromedae.	1 57.8	+41 51	2.3	2.8	K0	A	.070	10.7
ω Eridani.	3 49.2	- 3 14	5.0	1.4	G5	B?	.034	6.9
H.R. 1771.	5 17.7	-24 52	5.5	1.2	G	A3	.029	3.0
H.R. 2174.	6 3.8	+ 2 31	5.9	1.1	A0	B9	.027	28.9
14 Lyncis.	6 44.2	+59 34	5.8	1.2	G	A	.047	0.4
μ Can. Maj.	6 51.5	-13 55	5.4	3.1	K	A	.007	2.3
γ Volantis.	7 9.6	-70 20	3.9	1.9	K0	G	.097	13.3
H.R. 3428.	8 34.6	+20 1	6.4	0.5	G	A2	.041	63.4
ϵ Cancr.	8 40.6	+29 8	4.2	2.4	G5	A2	.054	30.6
24 Comae Ber.	12 30.1	+18 56	5.2	1.5	K0	A3	.017	20.6
H.R. 4893.	12 48.4	+83 57	5.3	0.5	A2	A	.033	21.6
α Lupi.	14 30.8	-45 42	5.6	3.3	K0	A	.034	19.8
ϵ Boötis.	14 40.6	+27 30	2.7	2.4	K0	A	.049	2.8
δ Boötis.	15 11.5	+33 41	3.5	4.5	K0	G0	.155	104.8
α Scorpii.	16 23.3	-26 13	1.2	5.8	Ma	A	.034	3.2
H.R. 6575.	17 34.1	+ 2 5	6.4	1.1	K	F5	.048	111.2
H.R. 6803.	18 5.7	+16 27	6.5	1.1	F	A	Small	1.2
H.R. 7140.	18 51.2	+33 51	6.1	1.7	G	A	.011	45.5
H.R. 7300.	19 10.8	+14 54	5.7	2.1	G0	A0	.020	89.9
β Cygni.	19 26.7	+27 45	3.2	2.1	K	B9	.009	34.7
χ Aquilae.	19 37.9	+11 35	5.6	1.2	F5	A	.013	0.6
H.R. 7548.	19 44.7	-55 13	6.1	0.6	G5	A2	.025	23.0
σ^1 Cygni.	20 10.5	+46 26	3.9	3.2	K	B8	.002	107.1
β Capricorni.	20 15.4	-15 6	3.3	2.8	G0	A0	.028	205.2
- Cephei.	22 18.8	+66 12	7.1	1.0	G	A	.042	4.1
H.R. 9094.	23 57.5	+65 33	6.0	1.5	F5	A2	.018	15.0

(brighter components) belong to the Classes F, G, and K, which have shown the largest average proper motions of any.

The average of the entire group is but 0".037, and if we omit the largest two (0".097 and 0".155) the average is reduced to 0".030. This criterion of proper motion indicates that these stars are at the same general distance as the stars of Class B.

The stars of Table II show a decided preference for the galaxy, half of them being within 15° , and three-fourths of them within 40° , of the galactic plane. This is significant when it is considered that the principal stars of these pairs belong almost entirely to the middle and later types of spectra.

Further evidence in this matter is found in 19 stars observed by Harvard College Observatory to have composite spectra and in 62 stars in Campbell's *Catalogue of Spectroscopic Binaries*,¹ in which the spectra of both components have been observed or strongly suspected.

For both spectra to appear on a photograph the difference in brightness of the components of close binary systems will usually be small. On account of the tendency for stars of nearly the same brightness to have similar spectra, the evidence from these two sources can scarcely be expected to be of as great weight as the preceding. It proves to be quite definite, however.

Of the 19 Harvard composite stars, 2 appear to be somewhat uncertain as to the differences of spectral class, both being of early type. Of the remainder the one having the largest proper motion ($0''.15$) has the fainter component of the later type. The remaining 16 all have very small proper motions. Of these, 5 have the fainter component of later type and 11 of earlier type. All of the most strongly marked spectral contrasts have the fainter components of earlier type, and all but one of the 11 are strongly marked with respect to spectral contrasts.

This evidence is confirmatory, therefore, of the condition noted among the double stars whose components had been separately observed.

Of the 62 stars of Campbell's *Catalogue*, 30 belong to types O and B and 23 to type A. It is reasonably certain, therefore, that all of the O and B stars are distant, and the probability is strong that most of the 23 A stars are distant also.

The following statement² I understand to apply to the 62 stars in question:

From the published descriptions of the double spectra it is fairly well established that when the two spectra are substantially equal in brightness

¹ *Lick Observatory Bulletins*, 6, 46, 1910.

² Campbell, *Lick Observatory Bulletins*, 6, 47, 1910.

they are identical in type: and when one spectrum is considerably fainter than the other, the spectrum of the secondary is apparently of a slightly earlier type than the spectrum of the primary. There appear to be no exceptions to this rule, though the difficulty in the way of giving accurate descriptions of the fainter spectrum must be recognized.

As there is also good reason to believe that the great majority of these stars are distant, we are led directly to the conclusion that these stars, as far as they are competent, also confirm the previous evidence.

In addition to the stars of the Harvard list, for which the spectra of both components have been observed, I have examined several other well-known stars whose colors have been observed, viz., α Herculis, η Geminorum, γ Delphini, η Cassiopaeiae, ξ Boötis, β Cephei, and γ Leonis. These stars also show in general the same relation to distance as the Harvard stars. There seems room for doubt as to the spectral class which may correspond to some of the colors observed. For this reason it seems best to omit all such from the classifications until the spectra have been observed.

Careful consideration of the data seems to show beyond doubt that the relation observed is to distance alone (or coupled with low galactic latitudes). It cannot well be with the actual separations of the stars, for the range in that direction seems to be about the same in all of the groups. It can scarcely depend upon the differences of mass of the systems as indicated by the differences of brightness, for a similar reason. There is a difference in absolute magnitude between the two groups, the nearer ones being on the whole the fainter. But there is no direct evidence of a relation.

There appears to be a consistently smaller difference in brightness in the stars whose components are of the same spectral type and also of a smaller average absolute separation than for the stars whose components differ in spectral class only. The difference of brightness seems quite definite and consistent, and seems to be corroborated in the cases of the stars with large differences of brightness, which show in general a large difference of spectral class also. The differences of separations are fairly marked for the groups, but are not very consistent. Both conclusions require confirmation from more extensive data.

The conclusion that the relations of spectral type in double stars of unequal magnitude depend in general upon their distance or, what is more probable, upon their location in our stellar system, seems to be shown so definitely as to leave no doubt of its reality. The data, although not extensive, seem sufficient, together with their consistency, to insure against mere coincidence.

We do not know the earlier condition of these double stars, whether both components were of the same spectral type or not. Investigators have generally assumed that the components were originally of the same spectral type. This appears to be the most natural assumption. It is not possible to say, therefore, just what the course of change has been. (That changes have taken place no one will doubt.) However, we can justly conclude, I think, that the conditions are such in these regions as to produce *opposite* spectral effects in the components. There can be little doubt that the fainter components are in general also of smaller mass. We may therefore state our conclusion in the following form: that the conditions appear to be such that if two stars of unequal mass were introduced into the near region the smaller body would progress more rapidly toward the later stage than the larger one, whereas in the relatively distant galactic regions the tendency would be for the smaller body to become of earlier type more rapidly than the larger one.

If the smallness of the absolute separations of the components of the same spectral type, which have been alluded to, should prove to be general, it would be evidence more or less strong that the spectral types of both components were the same at the time of their origin as binaries, and further that the middle types were more favorable to their formation.

The bearing of these phenomena on spectral classes in general will be considered in a later portion of this paper.

An attempt to trace the cause of spectral differences in the stars and nebulae.—In the history of the novae (imperfect as it is), particularly of Nova Persei No. 2, we have, it seems to me, a clue of inestimable value as to the course pursued by stellar bodies under conditions operating to produce the different types of spectra. The order in which their changes occur is at least *one* order in

which the greatest of nature's forces operate, and in fact the only order of such changes of which we have indisputable evidence. The novae give us the best (and perhaps the only) clue to changes under conditions which so far are impossible to produce in the laboratory. The belief gains force with me that the phenomena of the novae are not those of an isolated and very peculiar class of bodies only, but that their processes are closely related to the life-histories of all stars, the greatest difference being that they pass through their cycle in such an incredibly short time. Is not the fact that the various stages of the novae are paralleled almost perfectly by similar stages in the spectra of ordinary stars the strongest kind of evidence of the closeness of relationship in their essential processes?

It has been known for some time in a general way that stars of different spectral class preferred different regions, the solar and later types being most numerous in the nearer regions, whereas the early-type stars, particularly those of type B, show a strong affinity for more distant regions in the direction of the galaxy.

The peculiar dependence upon distance from the sun of the spectral relation of the components of double stars differing in brightness, which has just been discovered, adds considerable weight to the theory that spectral class depends very largely upon location in the system.

Dependence upon location in the system requires an external cause and does away at once with the sufficiency of universal natural laws alone, such as gravitation, radiation, contraction, electro-magnetic, and other forces. These may, and undoubtedly do, play important parts. But they are not the controlling factor. It is equally doubtful, in my opinion, that *variations* in such universal natural laws can be invoked, such as variable gravitation, peculiarities in radiation, contraction, etc., in different parts of the system. They seem unlikely. If there were no more reasonable explanation they might be. We have, however, I think, a more reasonable and probable cause, viz., that of cosmical matter. It is not difficult to understand how stellar bodies encountering sufficient of such matter may be caused to change their surface conditions (if no more) radically. We do not understand all of the

possibilities of such a condition and its results, but we have strong evidence not only that such matter exists, but also that it causes some such changes of spectral type. By a process of elimination as well as by direct evidence some such process has been tacitly accepted to account for the novae.

Distribution.—An examination of the galactic distribution observed by Pickering¹ of 6106 stars brighter than magnitude $6\frac{1}{4}$ shows practically the same (and nearly uniform) distribution for the stars of spectral classes F, G, K, and M, but a decided preference for the galactic regions is shown by the A stars, a preference which is strongly increased in the B stars. These results indicate not only a preference of B and A stars for the galaxy, but almost an equal *avoidance* by these classes of the non-galactic regions. These characteristics are well shown in Table III and Fig. 1, where the quantities have been reduced to percentages. The intermediate position of Class A is well marked.

TABLE III

DISTRIBUTION OF STARS BRIGHTER THAN MAGNITUDE $6\frac{1}{4}$ WITH RESPECT TO GALACTIC LATITUDE

	SPECTRAL CLASS						TOTAL
	B	A	F	G	K	M	
No. of Stars.....	716	1885	720	609	1719	457	6106
± 62.3	5	16	22	21	22	22	
± 39.8	12	18	21	21	22	24	
± 21.6	32	28	28	28	27	27	
± 8.1	51	38	29	30	29	27	

It is a well-known fact that nearly all of the novae, the stars of Class O, the planetary nebulae, the gaseous nebulae, and the short-period variables are found in the region of the Milky Way.

Distance.—Direct determinations of parallax are not available for the more distant stars and hence recourse is had to proper motions. It should be pointed out that Kapteyn and Adams' conclusion² that there is a direct relation between proper motion

¹ *Harvard Annals*, 64, 143-44, 1909.

² *Proceedings National Academy of Sciences*, 1, 14, 1915

and radial velocity tends to weaken the assumption as a measure of distance, but not to destroy it.

The proper motions taken from Boss's paper¹ show a marked decrease from the stars of Classes F and late A to those of Class B, indicating a general increase of distance also, as we approach the early B stars. This peculiarity is made plain in Table IV. The proper motions of the novae, the stars of Class O, the planetary

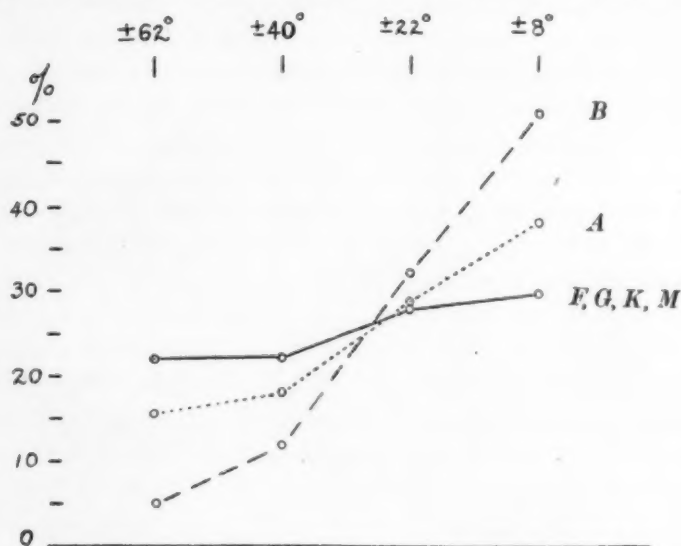


FIG. 1.—Galactic distribution by spectral classes

nebulae, and the short-period variables are very small. Hence their distances must be great.

The distributions and distances seem to confirm the belief that the more distant region in the direction of the galactic plane is the seat of conditions which tend to produce activity and a change of spectrum toward the earlier types.

Brightness.—Under this head will be considered: *a*) the absolute brightness of the stars of different spectral classes; *b*) the changes in brightness of the novae.

a) No exact figures are available to me of the average magnitudes and proper motions of the different spectral classes from which to

¹ *Astronomical Journal*, 26, 188, 1911.

derive relative absolute magnitudes. The general condition is, however, well known from the researches of E. C. Pickering,¹ who states with regard to stars of Class B: ". . . indicates that of the bright stars one out of four belongs to this class, while of the stars of the sixth magnitude there is only one out of twenty, and that few, if any, would be found fainter than the seventh or eighth magnitude." This appears to have a deep significance. Why are the B stars so few and all so bright?

TABLE IV
MEAN PROPER MOTION OF STARS BY SPECTRAL CLASS

	Number of Stars	Mean Centennial* Proper Motion
Oe5 to B5.....	490	2.40
B8 and B9.....	217	3.82
A.....	1157	4.62
A2 to A4.....	273	5.53
A5 to A8.....	164	7.07
F.....	287	7.91
F2 to F8.....	205	7.93
G entire.....	444	5.24
K entire.....	1227	5.74
M entire.....	222	4.99
Total.....	4686

* Excluding proper motions greater than 20" per century.

With regard to the A stars, a consideration of their average brightness and their proper motions seems to indicate an average intrinsic brightness for them greater than for the stars of later types and intermediate between them and the B stars. A consideration of their spectra also indicates a gradual diminution in brightness after the B class.

With the exception of γ Argus and ζ Puppis, all of the stars of Class O are relatively much fainter than those of Class B or other spectral types. There is good reason, therefore, to conclude that stars in the stage of Class O are, on the whole, very much fainter than stars in the stage of Class B.

There is also reason to believe that unless the planetary nebulae are enormously remote their absolute brightness is much less than

¹ *Harvard Annals*, 56, 37, 1905.

that of the O stars—that there is a sudden decline in brightness from B to O stars and a further decline to the planetary nebulae.

b) In Nova Persei No. 2 maximum brightness occurred at about the time it reached the B stage, from which it declined sharply as the bright-line stage appeared. Between the bright-line stage and the nebular stage there was a further and greater decline in brightness. In no other novae were spectroscopic observations obtained before the bright-line stage, but in all which were sufficiently observed the loss of light was very marked between the bright-line “nova” stage and the nebular stage. Considering, therefore, changes in brightness, the order appears to be the same in the novae as in the early spectral classes in the direction B, O, planetary nebulae.

Spectral changes in the novae.—With the exception of Nova Persei No. 2, the novae have not been observed spectroscopically until after the appearance of the bright bands. These emissions embrace hydrogen, helium, calcium, sodium, and a substance giving lines at $\lambda\lambda$ 463 and 468 which form one of the chief characteristics of the Wolf-Rayet or Class O stars. These emissions are often wide and distorted, probably more or less in proportion to the magnitude of the outburst, if we may judge by the brighter nova in Perseus, and are usually in pairs, an absorption line on the more refrangible side of an emission line. The strong, more or less continuous spectrum which is present at these stages gradually disappears and the lines characteristic of the nebulae make their appearance. The lines which are highest in the spectrum, particularly those at $\lambda\lambda$ 339 and 346, in some of the novae at least, were the last to appear and the first to disappear. This, together with the peculiar behavior of the bright lines of hydrogen and helium in early-type stars and the well-known shifting of the maximum of intensity in the ordinary incandescent spectrum with temperature, gives rise to the belief that the activity in these stars is progressive with wave-length and that the chief factor in these spectral changes is temperature.

With the fading of the continuous spectrum and general loss of light comes the nebular stage, when the condition of the nova is essentially a stellar planetary nebula. With continued loss of

light the pronounced nebular characteristics gradually disappear and the Wolf-Rayet conditions again become dominant. Finally some one of the ordinary stellar stages is reached as the star becomes very faint.

The more or less empirical explanation of the preference of B stars for the Milky Way and the relation to evolution in general rests very largely upon the behavior of Nova Persei No. 2. It is necessary, therefore, to review the early stages of this star briefly.

We do not know its early history further than that it must have been extremely faint previous to its very sudden outburst. Of its spectrum we know nothing until its observation on February 22, 1901, when it was of Class B, with typical hydrogen and helium absorption. This general condition it maintained through February 23. Between February 23 and 24 the great change occurred which placed its spectrum in the same class as the other novae previously observed.¹

With its later well-known bright-line history we are not especially concerned, as it was essentially that followed by these stars as a class. It is most unfortunate that we have no earlier observations of the spectrum of Nova Persei which would enable us to say definitely what stages it had passed through on its way from obscurity to magnificence. Such a course may or may not have been in the inverse order to the generally accepted order of evolution, i.e., B, A, F, G, K, M. It may be doubted, however, if any stage "later" than A appears in the early stages of novae on account of the rapidity of the increase of light.

However this may be, we have the definite fact that at about the time of its maximum brightness the nova was of spectral class B, from which it passed over very rapidly to the banded spectrum of the typical nova, with some characteristics in common with the bright-line stars, and finally became essentially a nebula.

Observations by Hartmann² in 1907 and by Adams and Pease³ in 1913 show that it had lost the strong nebular characteristics and again become a Wolf-Rayet star of magnitude $12\frac{1}{2}$.

¹ *Harvard Annals*, 56, Pt. 3.

² *Astronomische Nachrichten*, 177, 113, 1908.

³ *Astrophysical Journal*, 40, 294, 1914.

Probable cause of the outburst in the novae.—The various theories to account for the phenomena of the novae have, with one exception, been found wanting and have been abandoned. The one exception is that proposed first, I believe, by Monck¹ (and perhaps others), and elaborated by various investigators, which, although not conceded in all the details worked out from it, has been generally accepted, I think, as the most probable basis upon which to build a detailed theory. As time passes and data accumulate, the underlying assumption of this theory appears to gather strength, and I have little doubt that ultimately it will be found to satisfy observed conditions.

An attempt will be made at a future time to trace in some detail the action which takes place in the outburst and subsequent subsidence of the novae. For our present purpose it is only necessary to outline the theory in as simple a form as possible. It will only be assumed, therefore, that a body of stellar proportions has penetrated a mass of finely divided matter, and that the outburst has been caused by the conversion of kinetic into radiant energy. Nothing will be assumed as to the previous condition or movements of the stellar mass or of the actual condition of the cosmic matter. It is conceivable that such encounters may take place between stellar masses in all conditions with either finely divided solid matter, gaseous nebulae, or with a mixture of both, and that according to the conditions and masses of the bodies concerned we may have variations in the characteristics and duration of the resulting outburst.

In the case of Nova Persei the evidence favors the view that the finely divided matter was solid rather than gaseous before its encounter with the stellar body. The spectrum of some of the nebulosity, at least about the nova, was not gaseous, but resembled that of the star at about the time of its greatest brightness.² This is understood to mean that the matter was finely divided and solid and that it emitted no light of its own.

The fact that this type of spectrum occurred at about the time of maximum brightness of the nova is important and significant

¹ Clerke, *Problems in Astrophysics*, p. 379.

² *Lick Observatory Bulletins*, 2, 32, 1903.

in view of the apparent culmination of brightness generally in the stars of Class B.

In attempting to trace the action and relations in the novae it seems undesirable to lay much stress on small details and differences at the present time. In my opinion the larger and more important factors only should be considered in the first attempts to get a perspective of the true theory. Too much attention to small details at first (too near a view, in other words) is likely to prevent an adequate view of the whole. If we consider the tremendous forces which must of necessity be in action in such an outburst, what is more reasonable than to expect almost any kind of variation in the structure of such bands, the more violent the outburst the more complex the structure? Will there not be most terrific pressures, velocities, and abnormal distributions, particularly of the lighter gases? When I contemplate the magnitude of such forces I marvel that we should be able to recognize even hydrogen under such conditions.

The widening of spectral lines as an indication of activity.—Miss Maury¹ in her discussion of spectral types in the Draper Memorial has classified the 681 stars of that paper according to the width of spectral lines. She draws this conclusion: "It is therefore probable that spectra distinctly belonging to Division *b* (wide lines) are confined to stars of the Orion type and of Secchi's first type," i.e., to spectral classes O, B, A, and early F. A number of the brighter southern stars of these early types have been observed here recently, and one of the most suggestive things about their spectra is this peculiarity of narrow and wide lines. The wide lines appear to be especially significant, for in many cases they show a tendency to have bright borders. Practically all of them have the appearance of being the result of unusual activity, similar to the novae, only on a much reduced scale. It was so striking as to attract my attention to essentially the same conclusion arrived at by Miss Maury before I was aware of hers.

The greatest significance appears to be that this characteristic of broad disturbance lines, if we may call them such, is only found

¹ *Harvard Annals*, 28, 10 (Table I).

in the spectral classes which show the greatest preferences for the Milky Way, B and A.

There is another peculiarity which appears to be related to this widening of the lines in the early type spectra. It is the frequent occurrence of bright edges to the lines, both wide and narrow. These brightenings are more often of both edges of the lines, but sometimes are of only one edge, or one edge is much brighter than the other. They have been noticed in a large number of cases, and in many others very weak brightenings have been observed without any absorption. These phenomena give rise to the belief that they indicate unusual activity in the atmospheres or photospheres of these stars.

The characteristics and distributions of these stars are not due to pure chance. Interpreted directly they tend to confirm the theory that there are two courses being pursued in these early types and also that the underlying cause is largely due to some special attribute of the Milky Way.

Are the two sets of spectral lines due to an upward and a downward course as regards activity? Or are they due to two classes of stars differing widely in mass in some such way as the component stars of the globular clusters?

An examination was made of the proper motions of the stars whose lines were known to be wide, to see if they would show evidence of being more distant than the average stars of their respective classes. So far as the evidence from the few stars available goes, these stars appear to be at essentially the same distances as the other stars of the same spectral classes.

The distribution of these wide-line stars with respect to the galaxy was also examined. There appears to be no peculiarity in this respect beyond their spectral classes—the distribution of these wide-line stars is essentially that of the respective spectral classes to which they belong.

The maximum intensity in spectra and its relation to spectral order.—Another consideration which seems of importance in this connection is that of the intensity of different parts of the spectrum as an index of stage in evolution. An examination of the behavior of hydrogen and helium indicates that increasing activity is accom-

panied by progressive increase of intensity toward the violet, decreasing activity acting in a contrary way. Some of the elements present in the nebulae have been found to behave in a similar way. These, coupled with the well-known fact that in an incandescent source a rise or fall of temperature is accompanied by a shifting of the maximum of intensity in the spectrum toward the violet or toward the red, respectively, lead to the conclusion that the continuous spectrum alone furnishes an independent method of arranging the stars in order of activity. Now it is well known that in the order B, A, F, G, K, M the intensity of the upper portion of the spectrum continually diminishes. I have examined a number of spectra of Class O and find that the continuous spectrum in these stars, although weak, appears to be relatively stronger than in the B stars and much stronger than in the A and later types. This tends also to confirm Pickering's conclusion¹ that the fifth-type stars, Class O, form a connecting link between the B stars and the nebulae. It seems to me that this conclusion is still further strengthened by the intensity and activity in the higher parts of the spectrum of the nebulae.

The cause of Cepheid variation.—The fact that the Cepheid variables are distant and show a marked preference for the Milky Way raises the question whether the cause of their variation can be related to the conditions under discussion. The most important condition to be accounted for in this type of variation is that the maximum brightness occurs at approximately the time when the star is approaching the observer with its maximum velocity, and the minimum of brightness at the time when the star is receding with its maximum velocity. The spectrograph shows these stars to be binaries whose masses are widely different.

A number of hypotheses have been proposed to account for this type of variation.² The finding of evidence of action in distant galactic regions due to external matter has suggested an alternative

¹ *Astronomische Nachrichten*, 127, 1, 1891.

² The author proposed a hypothesis also on the ground of increased activity of the secondary after periastron passage (*Astrophysical Journal*, 41, 307, 1915). It was afterward found that a similar explanation had been proposed by Roberts twenty years before (*ibid.*, 2, 283, 1895).

cause of this type of variation. It is that the advancing faces of both stars will encounter a larger amount of such matter and become brighter in general than the following faces. If the two components were of equal size and mass, little or no variation in their total light would result. But as there is such a marked difference, at the time of approach of the primary such an increase of light due to its advancing face being turned toward the observer will be greater than the corresponding diminution due to the receding and darker face of the smaller star being turned in the same direction. The contrary would occur at the time the two stars were in the opposite parts of their orbits, i.e., the primary receding when the minimum of brightness occurs. If this is true, then the amplitude of the variation in brightness should depend upon the relative sizes and masses of the two components. To test this point the stars of this class whose orbits have been computed were examined. The result was indeterminate, owing perhaps to the small changes in brightness of these stars and to other factors which may be conceived to modify the results, such as density of matter, for example. A cursory examination of available data seems to indicate that the great majority, if not all, of the stars of great contrast in mass are of types B, A, F, and G, the short-period variables being confined to Classes F and G.

The matter seems well worth a close investigation as a possibly decisive test of the cause of this type of variability as well as for other bearings which may exist.

The foregoing explanation of Cepheid variation implies (what has been observed) that only binary stars of widely different masses can in the early spectral conditions show a periodic variation in brightness.

In this connection arises the very important question as to whether there is any physical relation between the Cepheid variables and the long-period variables of the late types which show bright lines at maximum. The marked differences in behavior of these two kinds of variables, coupled with their great difference in spectral type and with the fact that one group shows a strong preference for the Milky Way, whereas the other shows no such preference, seem to justify the conclusion that their activities are due to fundamentally different causes.

Some consequences of unusual interest would follow from the presence of considerable quantities of finely divided matter in the regions of double stars. For example, such matter would act as a resisting medium, and with the lapse of time the periods of these stars would become shorter. It appears to be significant that there is a progressive preference of the stars of early type for short periods.¹ Should such retarding action continue long enough we should expect the secondary body finally to be driven down upon the primary. What would be the result? It could hardly be a nova, whose disturbance must be very superficial and thin. Could it be a catastrophe of the magnitude to form the large gaseous nebulae?

As the hypothesis of cosmic matter in the Milky Way to account for the novae and the B stars appears to have a wide bearing, an attempt will be made to see if it will satisfy the observed spectral differences among the stars generally.

No attempt is made to account for the complete evolution of the system in the broadest sense, but only for the present cycle of changes and conditions. This may be only a limited portion of the total history, but nevertheless it appears to be more or less self-perpetuating.

The chief facts may be recapitulated as follows:

1. The strong preference of the B stars for the Milky Way, and their considerable distance.
2. The great absolute brightness of the B stars, and their small number.
3. The intermediate position in both respects of the A stars.
4. The strong preference of the novae, the O stars, the planetary and gaseous nebulae, for the Milky Way, and their distance.
5. The appearance of the B spectrum in Nova Persei No. 2 at the time of its greatest brightness.
6. The strong preference of the phenomena causing the outbursts in novae for the Milky Way.
7. The almost identical courses, both as to spectrum and relative brightness, followed by the novae and brighter stars, if arranged in the order B, O, planetary and irregular nebulae.

¹ Campbell, *Lick Observatory Bulletins*, 6, 38, 1910.

8. The broadening of spectral lines which is confined to the classes A, B, and O. This can scarcely be interpreted in any other way than as a sign of great activity.

9. The chief characteristics of the Cepheid variables—preference for galaxy, great distance, movement of maximum of intensity in spectrum toward violet at time of greatest brightness.

10. The dependence of the relation of spectral type of the components of double stars upon distance.

The foregoing facts, in connection with the course followed by Nova Persei, lead to the theory *that the stage of Class B in stellar spectra results from the same general cause as the similar stage in Nova Persei, and that the principal difference in the two cases is one of intensity affecting the element of time.* In other words, that the B stars are confined in general to the Milky Way, because there the conditions are favorable to the production or maintenance of that spectral stage in a manner allied to the outbursts of the novae.

This explanation appears to satisfy all the best-established facts, requires no violent assumptions, and on the whole appears to have a good degree of probability.

It is true that the preference of the B stars for the Milky Way may be explained also by evolution from the gaseous nebulae which are limited to the galaxy, and that the absence of the B stars in the nearer regions of sky may be naturally explained by assuming that all the stars in this region are older. The great brightness and small number of the B stars, the peculiar behavior of the double stars in the near and distant regions, together with the many signs of activity among the early-type stars in the galaxy, seem to indicate decisively, however, that the course of evolution in the brighter, early-type stars is toward the nebulae rather than away from them. The notorious fact of the great brightness of the B stars points clearly to the upward stage as the one to which they belong.

One of the strongest arguments for such a partial theory of the evolutionary processes as that indicated here is the number of previously disconnected facts which it appears to harmonize. For example, it not only explains the preference of the B stars for the Milky Way, but also explains the intermediate position of A stars, the greater distance and brightness of the B stars, the preference

of solar types for the region of the sun, a logical connection of the early spectral types including the planetary and irregular gaseous nebulae, the relation of the novae to ordinary stellar processes, and provides the basis for a simple and logical cycle of changes for the greater part of our stellar system.

Such an evolutionary process suggests a possible explanation also for the general preference of the bright stars of later types for the galaxy. It is simply that they are in general of larger mass, having swept up the matter which has always been most plentiful in the near as well as the more distant galactic regions, thus retarding development toward the later and fainter types.

The sudden decrease in brightness between the average B and the average O stars is very suggestive when compared with the great loss of light which occurred in Nova Persei about the time that, and shortly after, the bright lines and bands made their appearance.

It is true that the theory depends largely upon a stage of spectral activity which has been observed in but a single star and is incomplete. This one case is so definite, however, that taken in connection with other facts there seems good reason to think that a somewhat similar stage may have been passed through in the other novae before they became known. It seems all the more probable that such a stage may have escaped detection in other novae because of its early appearance and short duration.

However this may be, the evidence as far as it goes is very definite on the appearance of the B stage at or just before the maximum brightness is reached, and there is nothing to contradict the possibility that such a stage may be general in the novae.

Further consideration shows that it does not seem necessary to assume that all stars so affected would reach the bright-line stage of the novae or even the B stage; that if the changes depend upon the density of the cosmical matter (or other conceivable conditions) we should expect that the region of more sparsely distributed cosmical matter would be much more extensive than the regions of great density. It is perhaps significant in this connection that the number of A stars is so much greater than of B stars, which are in general undoubtedly of greater brightness. It seems not

impossible that those stars which only reach the A or B stage after the maximum pursue a decline through more or less the same stages as on the rise. Such a condition would account also for a large part of the observed excess of A stars over B stars.

Analogy in the case of the novae points to the very faint stars rather than the bright stars as being the returning stages to obscurity.

This hypothesis rests upon three assumptions as a result of the foregoing discussion:

1. That the spectral class of the stars is determined *in general* by location in the system, being a function of galactic latitude and distance.

2. That the more distant regions in the direction of the galaxy contain a larger quantity of finely divided solid matter than the near regions.

3. That the cause underlying the spectral changes among the stars is essentially the same as that producing the phenomena of the novae.

Hypothesis.—The general hypothesis to account for the present spectral conditions of the stars may be stated as follows:

The cause is dual, depending upon the amount of cosmic matter and upon radiation and condensation phenomena. The stars of Classes A, B, and O, the planetary and irregular nebulae, the novae, and perhaps the Cepheid variables, are confined to the galaxy because there the matter is sufficiently plentiful to cause an increase of energy, the energy from the matter swept up being in excess of the energy lost by radiation. The direction of spectral change under such conditions is *toward the nebulae*.

In the regions (distant or near) where there is little or no cosmic matter radiation will overpower the energy received from external sources and the direction of change will be *toward the late types*.

In a considerable portion of the system the changes of spectral class may be due to retardation.

The close relationship between the Wolf-Rayet stars and the planetary nebulae has been shown by the work of E. C. Pickering, Keeler, Wright, and others. The close connection of Class B and Wolf-Rayet stars has also been shown, particularly by the

work of the Harvard astronomers. There can be little doubt that the Wolf-Rayet stars belong between the nebulae and the B stars. The question is, In which direction has the change occurred? The course followed in the novae indicates very strongly that the nebular condition is the climax of evolutionary activity. If this be so, we have in the novae the general course of evolution pursued in regions where cosmic matter is plentiful.

Briefly stated, it is that essentially stellar bodies encounter cosmic matter in the form of clouds;¹ that these encounters produce disturbances in the star's atmosphere, or, what seems equally possible, the formation of an atmosphere on a solid body; that the stage of spectral type reached will depend upon the masses of matter concerned and the violence of the encounter, the most violent encounters reaching the nebular stage, on the way to which the body passes the stage of Class B, then of Class O; that the planetary nebulae are the relatively moderate outbursts in which gaseous nebulosity has been generated, whereas the large irregular nebulae have resulted from the most violent outbursts of all; that the declining stages are pursued in a more or less inverse spectral order to that of the rise; that the increasing stages of activity and the culmination are, in general, marked by a broadening of the lines and bands, both of absorption and emission, possibly in the larger masses only, and that the declining stages are marked in general by narrow lines.

Hypothesis to account for the planetary nebulae.—If the order of evolution proposed above is correct, a not improbable explanation of the formation of the planetary nebulae presents itself. It is that the outburst, if of sufficient violence, may pass beyond the ordinary Wolf-Rayet stage and evolve a large amount of gaseous nebulosity which is thrown off as a shell. Such a shell will appear as a more or less circular ring with a web of faint nebulosity inside the ring, and a central star. The detail within the rings, which is remarkably varied, can be accounted for as streamers and irregular masses thrown out from exceptionally disturbed areas on the star,

¹ It may be possible that an encounter with purely gaseous matter may produce similar phenomena. On the whole it seems much more probable, in my opinion, that the encounters have been with finely divided matter in a solid state.

much as we account for the streamers and masses of the solar corona.

This explanation seems to imply that the forces acting on the nebulosity ejected reach their limit at the outer edges of the ring. The outward forces I conceive to be eruption and light-pressure, opposed by gravity. Combinations of these appear to be sufficient to account for the observed phenomena.

Electromagnetic forces may play a part also, but of their presence or action in such cases we know little at present.

If this be the process of evolution of the planetary nebulae, then a central star *must have been* a necessary factor. It does not follow that it is visible now. Indeed such an origin would lead us to expect some of the brightest central stars to be found in the smaller or fainter nebulae, where the activity may have been less than in the large or bright objects in which the activity might be expected to have been greater and the material of the originating star more completely dissipated. The complete absence even of such a central star in some of these bodies can be accounted for in this way.

Hypothesis to account for the irregular nebulae.—If the initial outburst is great enough, the gaseous nebulosity will be driven off, both by the force of the outburst and by light-pressure, at a speed which will overcome the attraction of the central mass and carry to great distances. It would seem logical in such cases to expect less regularity in form of the resulting nebulosity than in those where the activity has not been so great.

This leads to the suspicion that the dark, finely divided matter which is believed to exist in the distant galactic regions may be none other than such condensed nebulosity—that in place of the early Orion stars, for example, being wholly in the process of condensing from their inclosing nebulous envelope, this nebulosity is in fact largely the *result* of a great catastrophe, the nebulosity having been thrown off in the process.

Is this also true of the nebulosity in the Pleiades, with the difference that in the Pleiades the stars are slightly "older" in type and the nebulosity not self-luminous? Has this nebulosity frozen from a gaseous state? It is very suggestive that many

bright stars of early type have masses of nebulosity near, which appear to be connected with them.

Upon this hypothesis the effect on double stars would be somewhat as follows: The smaller bodies, because of their larger relative surface areas, will sweep up more of this matter than the large ones in proportion to their masses. If we assume that the increase of energy is greater by such accretions from external matter than the energy lost by radiation, the activity (temperature probably) of the smaller body will increase more rapidly than that of the large body. If, therefore, the two bodies start in the same condition, the smaller should move more rapidly toward the early type of spectrum. This, of course, implies that the effect in these stars is not merely a surface one.

On the other hand, in the near regions such a hypothesis accounts for the change of spectra of the secondaries toward later types by assuming that radiation is greater than the energy absorbed from the external matter.

The stars whose components are of the same spectral class show much smaller differences of magnitude than do the other groups and an almost complete limitation of such as have small proper motions to Classes B and A. These peculiarities, as well as that of the pairs of small μ in which the fainter star is of the later type, do not appear to be contradictory to the hypothesis given. Two stars of the same size acted upon by the same conditions should leave them of the same class still, even if they were in the region rich in cosmic matter. On the other hand, in distant regions where matter was not so plentiful the smaller and fainter star of a pair would be of later type, just as appears to be the case in the nearer regions.

The evidence of these double stars seems to show that no considerable portion of the supposedly high surface temperatures of the early-type stars can be due to the working of Lane's law. No such law can reasonably be supposed to be selective in its action.

Many questions suggest themselves in this connection. Does the bright-line stage in the early-type stars mark the culmination of their activity? Or is it merely an accidental phase?

What part does the matter composing the zodiacal light play in the spectral condition of our sun? If it were not for this matter, would our sun be of K type or later?

If such is in reality the chief cause of the differences in spectral type, may it not be that the changes in many of the early-type stars occur in relatively short intervals?

What is the relation of the globular clusters to the other members of our stellar system? How have they been formed? Why are the component stars so uniform in brightness and type?

The recent researches of Nicholson seem to me to have a bearing on the conditions underlying spectral changes in general, but particularly of the Wolf-Rayet stars and the gaseous nebulae. May not his conclusion that the spectrum of coronium is that of a substance known on the earth which has been raised to incandescence by some special method of excitation be extended to substances raised to super-temperatures such as appear to exist in the gaseous nebulae?

Some three or four years ago the idea came to me that some such conditions best satisfied all of the principal known facts and that the few observable radiations in the spectra of the nebulae might be due to the high temperature of these bodies (combined perhaps with electromagnetic forces), where the greater part of the energy had been pushed out, as it were, at the upper end of the spectrum, where the atmosphere and the weakness of our observing methods make it nearly or quite impossible for us to detect its presence. This idea has not weakened as time passes. The facts surrounding the appearance of the nebular spectrum in the novae seem to me a strong argument for some such condition.

The question arises whether it is possible, under the conditions believed to exist, for development of stellar bodies to take place from masses of gaseous nebulosity in the way which is usually assumed, i.e., by condensation and accumulation of the nebulous matter itself. For were a nucleus to be formed in the mass of gas, would not the accumulation of some of the surrounding nebulosity and its condensation upon this nucleus, according to Lane's law, cause a rise of temperature which would again disrupt the mass until an equilibrium of temperature was reached, then to go through

a similar cycle, but without the possibility for a body of any considerable size to be formed *from the inside*? Formation through condensation and radiation from the outside also seems to present some difficulty.

If temperature is the dominating factor in stellar activities and conditions, as there is strong reason to believe, and the nebular condition is the culminating form of matter as temperature rises, as appears to be the case judging from the novae, some rather curious consequences appear to result from the application of the theory of evolution from the gaseous nebulae. According to Lane's law the temperature will rise in the gaseous mass as soon as condensation sets in. If this happens, what form will the nebulosity take with the increase? Would it not have to take some "super" form, of which we appear to have no knowledge? If this reasoning is correct, how can a mass of gaseous nebulosity ever condense as such? This seems to lead to an *impasse*—either Lane's law is not true in such cases, or the gaseous nebulosity must change its form or condition in some manner before again playing a part in condensation phenomena. Perhaps the nebular stage is not strictly a gaseous condition.

General condensation does not seem to harmonize with the observed conditions, which are that the great nebulous masses have one or more large and often bright stellar bodies within or nearly centrally located in the nebulous mass. It is possible to see how the nebulous matter has been largely or wholly ejected from the stars, but not how these stellar bodies have been formed wholly from the nebulous masses.

A most suggestive conclusion has recently been reached by Seares.¹ From photographs taken with and without a color-filter he found that in several spiral nebulae the outer regions in general and the more dense condensations in the spirals had a larger proportion of light of shorter wave-length than the central regions of these nebulae.

The significance of this observation in the present case lies in the fact that a considerable number of very bright B stars or a general tendency to the early type of spectrum in the bodies of the outer

¹ *Proceedings National Academy of Sciences*, 2, 553, 1916.

galactic regions of our system would tend to produce some such effect as that observed by Seares. The researches of Pickering¹ and Kapteyn² show exactly such a condition for stars down to the tenth magnitude. Although the stars fainter than this have not been investigated, it seems probable that this effect may continue to fainter magnitudes also.

Conclusions.—The results of this investigation may be summarized as follows:

1. The relation of the spectral classes of the two components of a binary system is a function of distance from the sun, those at distances generally beyond $\mu = 0''.05$ (excepting some stars with both components of Classes B and A) having the fainter components of *earlier* spectral type, while those nearer have the fainter components of *later* type.

2. The preference of the B stars for the galaxy can be explained upon the assumption that they have passed through stages similar to that of Nova Persei No. 2 at or just before its maximum brightness.

3. The foregoing phenomena can be explained as due to the same causes which produce the outbursts in the novae, viz., encounters with finely divided solid matter or gaseous nebulosity or both.

4. Such a hypothesis, if confirmed, has a bearing on the order and cause of the evolutionary processes in our stellar system, and tends to substitute location and external causes for time as of the first importance.

5. The observed facts appear not to be inconsistent with the hypothesis that a large part of the characteristics of spectral class among the stars generally may be due to some external condition which is largely a function of both galactic latitude and distance, combined with phenomena of radiation and condensation.

OBSERVATORIO NACIONAL ARGENTINO, CÓRDOBA

October 31, 1917

¹ *Harvard Annals*, 26, 152.

² *Annals of the Royal Observatory, Cape of Good Hope*, 3, 22 (Introduction).

ADDENDUM

The list of luminosities and parallaxes of 500 stars, by Adams and Joy,¹ which has just come, contains 24 double stars and wide pairs with common proper motions, whose spectra for both components are given. These have an important bearing upon the part of the foregoing paper which deals with the variation of spectral class of the components of double stars with distance. The principal data regarding these 24 stars are collected in Table V.

These stars are practically all of large proper motion and the parallaxes show that most of them are near, as was to be expected. According to the criterion established in the preceding paper, essentially all of these stars should have the fainter component of later type. Of these stars twenty-one show such a condition; one (γ Virginis) has both components equal in brightness and of the same spectral type, and 2 show the fainter component to be of earlier type. Of the latter two, one (Boss 4892-3) has a difference of only 0.2 magnitude, a spectral difference of $3/10$ of a unit, and a moderate sized parallax. The other exception (ϵ Hydrae) has a large difference of magnitude (4.0), a small difference of spectral type for so large a difference in brightness, the proper motion is only medium sized, and the trigonometrical parallax small. The spectrographic parallax of the fainter component comes out rather small also (0".016). The other stars call for no special comment further than that the nearest and those of largest difference in brightness have also in general the greatest difference in spectral type.

These stars, therefore, confirm the previous conclusion that in the nearer stars the fainter component is of the later spectral type. Not a single one of these stars is really contradictory if we make a reasonable allowance for limits in which the transmission may occur. The small change of type in the case of ϵ Hydrae with so large a difference in brightness is not necessarily inconsistent with the theory proposed, as this star is in the region where the transition appears to occur.

This material addition to the data and the very valuable parallaxes make it possible to obtain some information regarding the distance at which the transition in relative type of spectrum of the

¹ *Mt. Wilson Contr.*, No. 142; *Astrophysical Journal*, 46, 313, 1917.

TABLE V*

NAME	VIS. MAG.		1000.0		SPECTRUM		ABS. VIS. MAG.		LUM.	μ	π	
	Br.	Fr.	α	δ	Br.	Fr.	Br.	Fr.			Spec.	Trig.
Σ 3062.....	6.9	8.0	α^h 1 ^{uo}	+57° 53'	G4	G9	5.2	5.3	0.832	0.266	0.046	+0.036
η Cassiopeiae.....	3.6	7.6	0 43.0	+57 17	F9	K4	5.0	8.7	1.00	1.242	.100	.101
Boss 592-3.....	6.6	7.4	2 31.2	+24 13	F3	F5	3.9	3.7	2.75	0.140	.028	.030
γ Leporis.....	3.8	6.4	5 49.3	-22 20	F7	K5	4.7	7.5	1.32	0.468	.151	.108
G Cancri.....	5.2	6.0	8 6.5	+17 57	F8	Go	3.4	4.1	4.37	0.155	.044	.031
ϵ Hydrae.....	3.5	7.5	8 41.5	+6 47	F9	F4	2.5	3.6	10.0	0.196	.003	.004
Fed. 1384.....	9.2	9.2	8 46.0	+71 11	K7	K8	9.2	9.7	0.021	1.40	.126	.086
Lal. 18115.....	7.9	7.9	9 7.6	+53 7	K8	K8	8.6	9.2	0.030	1.69	.138	.152
ξ Ursae Majoris.....	4.0	4.9	11 21.7	+32 6	F9	Gi	5.0	5.6	1.0	0.732	.158	.158
83 Leonis.....	6.5	7.6	12 36.6	+3 33	Go	K4	4.9	6.3	1.10	0.743	.048	.023
γ Virginis.....	3.7	3.7	14 40.8	-0 54	Fo	Fo	3.1	3.2	5.75	0.504	.076	.068
ξ Boötis.....	4.7	6.6	14 51.6	+19 31	G6	K3	5.5	7.6	0.631	0.168	.145	.230
Pi. 14 ^b 212.....	5.8	8.7	15 4.7	-15 54	K5	Ma	6.8	10.1	0.191	2.039	.158	.174
A.Oe. 14318-20.....	9.2	9.6	15 8.2	+19 39	G8	Ko	6.0	6.2	0.398	3.75	.023	.054
Lal. 27742-3.....	6.8	7.6	16 10.9	+34 7	G6	G9	3.9	4.9	2.75	0.68	.026	.018
σ Coronae.....	5.8	6.8	16 18.7	+33 56	F8p	F9	4.4	5.1	1.74	0.302	.046	.031
ν Cor. Bor.....	5.3	5.4	17 42.5	+27 47	K6	Ma	1.6	0.9	22.9	0.555	.018
μ Herculis.....	3.5	9.7	18 0.4	+2 31	G5	Mb	3.2	9.6	5.25	0.817	.087	.005
70 Ophiuchi.....	4.1	6.0	18 21.4	+8 44	Ko	K5	5.6	7.6	0.375	1.131	.200	.187
Gr. 10 Area II, 66.75.....	7.7	8.1	19 9.5	+49 40	G5	G8	0.3	4.3	1.91	0.498	.052	.037
Boss 4892-3.....	6.6	6.8	19 39.2	+50 18	G6	G4	5.5	5.5	0.631	0.054	.060	.052
Boss 5037-8.....	6.3	6.4	21 2.4	+38 15	G1	G4	5.3	4.4	0.759	0.217	.063	.048
61 Cygni.....	5.6	6.3	23 8.9	-9 28	K7	K8	7.9	8.7	0.069	5.271	.288	.313
Lal. 45455-6.....	8.6	9.0			F4	Go	5.1	5.8	0.012	0.56	0.020	+0.019

* The α , δ , Lum., μ , and π refer to the brighter components of the pairs.

components occurs, and of the rate of change of spectral type with difference of brightness. The condensed results are given in Table VI. It does not appear to be necessary, at this time, to give all of the individual results and the names of the stars.

TABLE VI

	HARVARD STARS			MT. WILSON STARS	
	Companion Earlier Type	Companion Later Type		Companion Later Type	
		Large μ	Small μ	Large π	Small π
Difference of visual magnitudes.....	1.9	2.6	1.8	2.1	0.8
Difference of spectra.....	-1.02	+0.63	+0.25	+0.34	+0.26
Mean μ	0 ^s c37	0 ^s 19	0 ^s c33	1 ^s 08	0 ^s 39
Mean π				0 ^s 164	0 ^s 044
No. stars.....	28	11	12	10	14

The pairs of both lists, in which the fainter components are of later type, were divided roughly into two classes, larger and smaller proper motions. There appears to be a relation between the differences of magnitudes and spectral type depending upon the size of the proper motions, the larger μ (nearer) stars showing a larger mean difference of magnitude and a larger variation of spectral type than the smaller μ (more distant) stars. There are reasons for thinking that this condition may be real, but the evidence as given in the table cannot be considered to have much weight because the mean μ of the Mt. Wilson group of *smaller* μ is double the size of the μ of the *larger* μ group of the Harvard stars. An examination of the presumably critical stars seems to confirm the reality of such a peculiarity. The results are shown graphically in Figs. 2 and 3.¹ The small range in spectral type for the smaller μ stars is very marked in Fig. 3, where all of them (26 in number) without exception have a range of spectrum of less than one unit,² and two stars have a small reversal of spectral difference.

¹ The black disks in Figs. 2, 3, and 4 represent Harvard stars; the open circles, Mt. Wilson stars.

² The unit is assumed to be equal to the spectral interval A₀ to F₀, F₀to G₀, etc., or G, 1, 2, 3, etc., to K, 1, 2, 3, etc., and is divided into ten parts to conform to the subscripts in the spectral classes.

On the other hand, the variation of spectral type with difference of visual magnitude is much greater in the stars whose fainter components are of *earlier* type, as is seen from Fig. 4. The reality

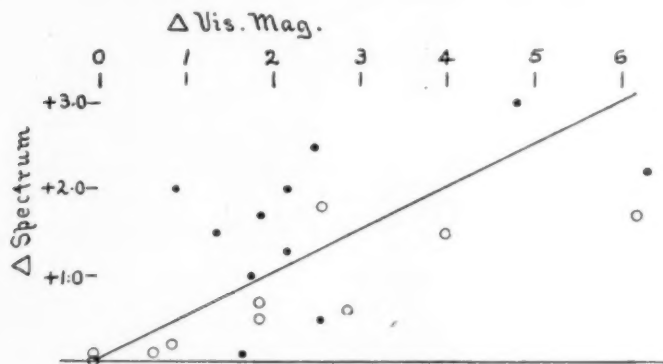


FIG. 2.—Curve of spectral changes, larger μ and π

of the large variation is confirmed by the stars showing large differences of brightness, which also show large differences of spectral class (where the effect of accidental error is much reduced). Only one star of large difference of brightness (δ Boötis) shows a small

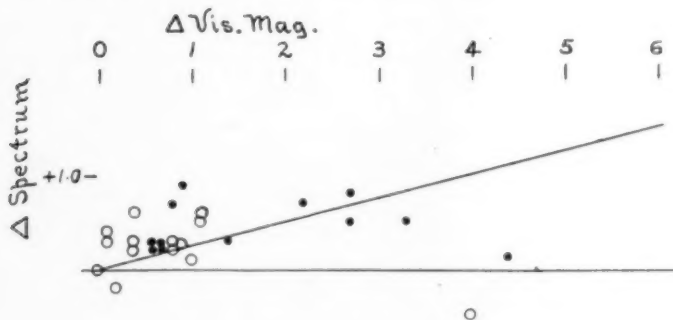


FIG. 3.—Curve of spectral change, smaller μ and π

difference of spectral type, and its comparatively large μ (the largest of the group) seems to place it in the region of transition. It should be said that the classifications were arbitrary without any suspicion that such a peculiarity might exist.

Fig. 5 shows the curves of the variation of spectral type with difference of brightness where the companions are of earlier and also of later type. For this purpose all of the latter stars were

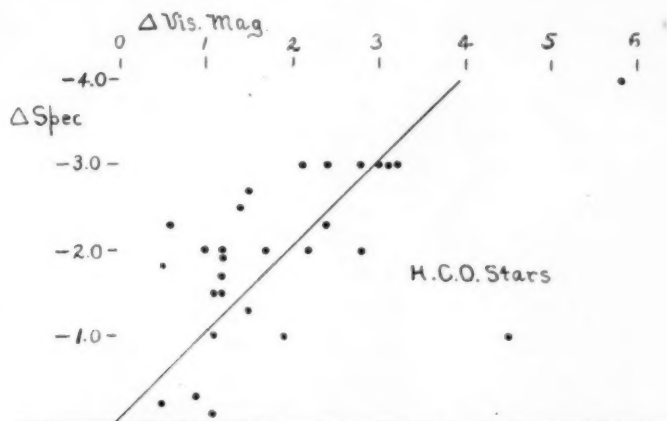


FIG. 4.—Curve of spectral change, companions earlier type

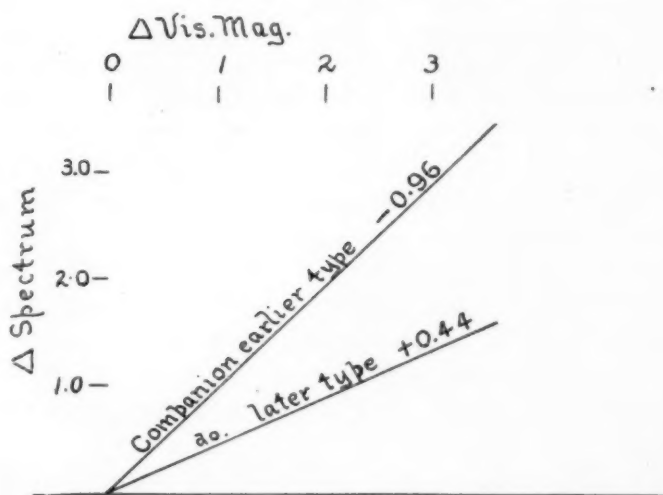


FIG. 5.—Curves of spectral change

combined. I see no reason to suspect that systematic differences in the determination of spectral class can have caused this rather consistent difference in rate of spectral change. It seems not

difficult to account for such a difference on the general hypothesis already formulated. Notwithstanding these presumptions in favor of its reality it seems best to await further confirmation before discussing it.

It is not probable that the distance is the same in all directions, but the data do not seem to justify an attempt to determine the law of distribution and distance. Such a knowledge would doubtless be very interesting and important, and as soon as sufficient data or a better knowledge of the matter is obtained it will be attempted.

After the completion of the earlier paper, an article by H. E. Lau,¹ "Über die blauen Doppelsternbegleiter," was received, in which he calls attention to the peculiarity of spectral relation of the components of double stars, and ascribes it to phenomena connected with "giant" and "dwarf" stars.

In any groupings of very large and very small proper motion, among the naked-eye stars, there will almost always be a large difference in absolute magnitude. This is the case with the stars in Lau's lists, the difference being 6 magnitudes or more. The differences are not so great in my own lists. On the basis of proper motions the difference in the case of the Harvard stars is not over two magnitudes. That this is not a phenomenon limited to giant and dwarf stars is clearly shown, in my opinion, by two things:

a) The peculiarity is found among all absolute magnitudes and among all spectral classes, as an inspection of Tables I and II of my paper shows.

b) Four stars of mean apparent magnitude 6.4 and $\mu = 0''.044$ were found among the stars having the fainter components of *earlier* spectral type and four stars of mean apparent magnitude 2.7 and $\mu = 0''.134$ among the stars having the fainter components of *later* type.

When reduced to a common distance on the basis of their proper motions, the stars of the group with the companions of *earlier* type are found to be a magnitude fainter than those of the group with companions of *later* type, thus reversing the giant-dwarf relationship assumed by Lau.

¹ *Astronomische Nachrichten*, 205, 29, 1917.

CONCLUSIONS

I. The 24 pairs of stars of Adams and Joy's Mount Wilson list of the luminosities and parallaxes of 500 stars fully corroborate the conclusion reached in the foregoing paper that the fainter components of such stars, when near, are of a later spectral type than the primaries.

II. The transitional stage where a change in this phenomenon takes place and the fainter components become of *earlier* type appears to be at a general distance represented by a parallax of $0''.01$ or $0''.02$, corresponding roughly to 200 or 300 light-years.

III. At the general distance assumed to be that of the transition of the fainter components from later to earlier spectral type there appears to be a smaller change of spectral type generally for a given difference of magnitude than is the case with either the nearer stars or those in which the fainter components are of earlier type.

IV. The change of spectral type for a given difference of magnitude appears to be less on the average in the stars having the fainter components of later type than in the stars having the fainter components of the earlier type.

OBSERVATORIO NACIONAL ARGENTINO, CÓRDOBA
February 13, 1918

KNIFE-EDGE SHADOWS

PHOTOGRAPHY AS AN AID IN TESTING MIRRORS

By RUSSELL W. PORTER

The characteristic and somewhat startling shadow (so called) that covers a paraboloidal mirror when a knife-edge intercepts the cone of light rays from its surface entering the eye affords one of the principal optical tests in determining the precise figure of the speculum in the reflecting telescope. It is a rather complex shadow to describe to one who has never seen it, and the attempts to depict it in treatises on speculum-making are deplorably weak in presenting the illusion of reality and give but little help to one anxious to figure his own mirror.

Such considerations as these led the writer recently to interpose a sensitive plate in place of the eye behind the knife-edge at the center of curvature of a concave mirror. It seemed reasonable to suppose that the shadow would in some degree be impressed on the plate; and after many failures, due for the most part to faulty illumination, he succeeded in securing the photographs accompanying this article. To his great surprise they revealed imperfections of the glass, unsuspected and unseen by the naked eye; and it was at once apparent that such photographs would be a great aid in the final figuring and provide a perfect guaranty of the optical excellence of the mirror.

Photographic records of optical surfaces of revolution have been obtained in the case of lenses by J. Hartmann, who investigated the 15-inch objective at Potsdam and the 40-inch of the Yerkes Observatory from photographs made at Williams Bay.¹ It would seem that the writer has been trying to do with the reflector what Hartmann had already accomplished for the refractor. There is, however, this difference: in the Hartmann "focographs" the plate is focused on the objective itself by the introduction of a camera lens, while the concluding photographs accompanying this account

¹ *Zeitschrift für Instrumentenkunde*, 29, 217, 1909; *Astrophysical Journal*, 27, 237, 257, 1908.

are secured directly without focusing, thus freeing the results of any errors due to the addition of another lens in the optical train.

The stand carrying the knife-edge and artificial star are shown in Fig. 1. At the left is a brass tube inclosing an acetylene flame, opposite which, attached to the tube, is a small slide carrying several

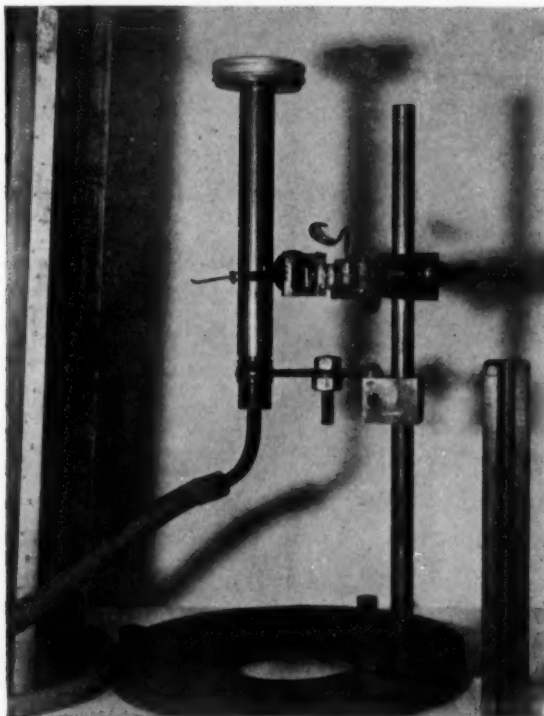


FIG. 1

perforations of diameters varying from $1/0.0005$ to $1/0.05$ of an inch. Between the tube and stand-support is seen the knife-edge inclosed in a square frame traveling on a track parallel to the optical axis of the mirror. Behind the square frame is a removable eyepiece for examining images in the plane of the knife-edge. Transverse motion of the knife-edge is obtained with the leveling screws on the stand base. Just above the knife-edge is a small magnifying glass used in keeping the knife-edge in its proper

position on the cone of reflected light during exposures. The camera is not shown in the photograph.

Following the method of Hartmann by focusing the plate on the objective by means of a telephoto lens, the series of focographs near the center of curvature were obtained (Plate VII). The mirror was 12 inches in diameter and 4 feet in focal length. The figures show in an interesting way how the characteristic parabolic shadow develops and changes from a position 0.15 inch inside the mean center to a like position outside.

In the experiment, doing away entirely with focusing and simply exposing the plate to the reflected cone, the photographs in Plate VIII were secured. The speculum used was one of the writer's first mirrors, of 10 inches' diameter. He had subsequently converted it to the Cassegrain form and bored out its center, as with the previous glass, without noticing any distortion of surface. He knew that there was a pronounced turned-down edge, but when this zone was diaphragmed out the performance of the glass was quite satisfactory and produced a creditable image.

The three upper focographs of Plate VIII are taken with the knife-edge at the center of curvature of the mirror, as in the lower left-hand diagram. The parabolic shadow is formed on the ground glass immediately when the knife-edge begins to cut into the cone of reflected light. By looking at the knife-edge with the magnifying glass, where the cone impinges upon it, it is easy to determine when it has reached the center of the cone section thus cut. The mean center of curvature can be found almost as readily on the ground glass as with the naked eye.

Focograph No. I was taken inside the center of curvature, No. III outside, 0.12 inch apart along the optical axis. No. II was intended to be at the center itself but is in reality, as the focograph shows, a little inside.

The character of these extra-focal negatives is beautifully brought out. Their respective apparent sections are drawn above them, assuming the light to graze the surface from the direction opposite to the knife. This is the remarkable delusion of Foucault's shadows—that the mirror seems to be illuminated by light coming in at right angles to the axis and not along it, as it really does.

PLATE VII

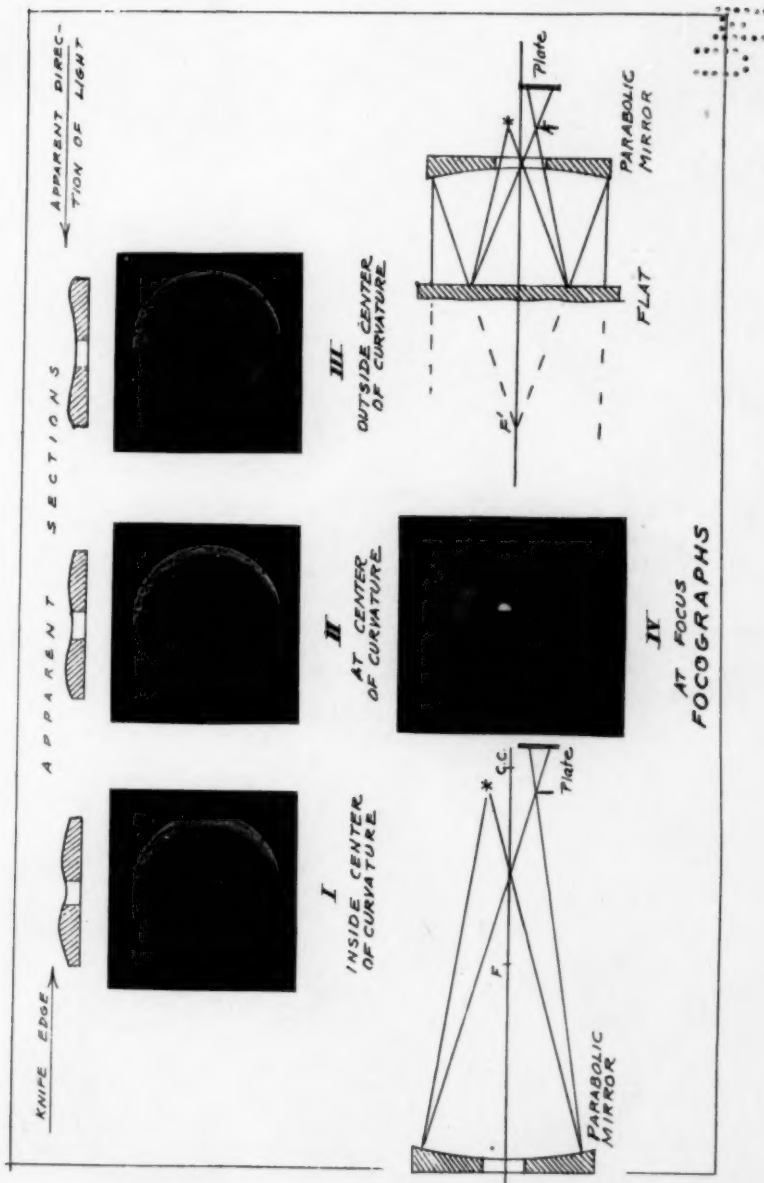


FOCOCGRAPHS NEAR CENTER OF CURVATURE

Taken from positions from 0.15 inch within to 0.15 inch outside the mean center

100000
100000
100000
100000
100000
100000

PLATE VIII



20000
20000
20000
20000
20000

Superposed over these parabolic shadows there is a faint trace of the characteristic shadow of a warped surface. The glass was not hung in a strap but rested on its edge. Distortion might be expected, and it is there and evident to the optician familiar with it.

Now as to the markings on the glass surface itself. Most noticeable is the turned-down edge. There was probably an attempt to rectify this by local polishing, which produced the small, round, intensely white spots seen strung along the rim. Next are the marks of the small rose tool, small epicycloidal strokes of the polisher hitherto unsuspected, and then the shadow coming in from the upper edge, also unsuspected and perhaps due to internal strains in the glass. Even the accidental scratches on the mirror are very noticeable. Finally one recognizes a slight turning up of the edge around the hole bored out of the center, which, as before remarked, could not be seen when tested with the eye after the disk had been perforated.

The lower and larger focograph was taken with the knife-edge and artificial star at the focus, midway between the center of curvature and the mirror. It might be obtained at the telescope by removing the eyepiece and keeping the image of a bright circum-polar star on an interposed knife-edge. But atmospheric disturbances and uneven driving of the clock would certainly render it difficult. In the laboratory, however, the best conditions are realized, and parallel rays are secured by the use of a flat, as shown in the right-hand diagram.

The optical train is as follows: The concave and flat mirrors face each other at a distance apart of about one-half the focal length of the former. Artificial star, knife-edge, and plate are behind the parabolic mirror. The beam of light from the pinhole strikes the flat, is reflected to the concave surface, and is thrown back to the flat in parallel rays. It returns to the knife-edge in the same way but in reverse order. There are in all five reflections, so that inequalities of the parabolic surface reach the plate exaggerated by double their true value. Much light is lost by absorption; hence for photographic purposes the mirrors should both be freshly silvered and a brilliant light source used.

Theoretically, with a perfectly parabolized concave and a perfect flat, light from a point-source will return by reflection to a point; and the interposition of a knife-edge at this point will

produce instant extinction. The point-source having the appreciable diameter of the pinhole (one-hundredth inch), obliteration of the disk does not occur at once, and the occultation takes place progressively through a uniform fading away of the illuminated disk. This is the condition striven for by the optician. Had the mirror under examination been perfectly parabolized, its focograph would have presented an absolutely flat disk. But the shadow indicates clearly that the mirror was overcorrected and that its defining qualities would be improved by refiguring.

The phenomenon of diffraction is well shown in these focographs. If a magnifying glass is used, fringes will be seen accompanying all the stronger markings.

It is also interesting to consider the minuteness of the quantities we are dealing with. This mirror was a long-focus one and the amount taken off its surface near the center, in passing from the sphere to the paraboloid, was something like one hundred-thousandth of an inch (0.00025 mm). In other words, the large shadow over the right side of focograph No. II is due to this depressing of the surface by this amount. The shadows of the depressions produced by the rose tool, for instance, are of an order very much less than that of the large shadow, say one-tenth, and indicate a departure from the true parabolic surface of only a few millionths of an inch.

Is it surprising, then, if such minute inequalities are so palpably sufficient to impair the defining qualities of a mirror, that larger departures from a true surface should arise through deformation by flexure due to faulty support? It is therefore important that these grosser distortions due to flexure and temperature be watched for and guarded against. If each night before getting down to work the observer will apply the knife-edge test with a bright star by removing the eyepiece, he can tell at once if his mirror is as it should be; if not, the character of the shadow will point the way to the source of the trouble. He will find it an excellent index to the state of the atmosphere, which, if unsteady, will make the mirror appear to boil like molten silver.

LAND'S END OBSERVATORY
PORT CLYDE, MAINE
December 1917

THE ORBIT OF THE SPECTROSCOPIC BINARY BOSS 46¹

BY WALTER S. ADAMS AND GUSTAF STRÖMBERG

The star Boss 46 = B.D. 50°46 ($\alpha = 0^h 12^m 4$; $\delta = +50^\circ 53'$, 1900.0) belongs to the class of spectroscopic binaries in which the calcium lines give values of the radial velocity differing widely from those furnished by the other lines in the spectrum. The variable velocity of the star was first found from spectrograms obtained in 1914 at Mount Wilson, and the announcement of the variation was made in the *Annual Report of the Observatory* for the year 1916. The visual magnitude of the star is 6.0 on the Harvard scale; its total proper motion is $0''.011$ annually; and its spectral type as determined from our photographs is B3p. The lines in its spectrum, with the exception of those due to calcium, are faint and diffuse, and a spectrograph of low dispersion has been employed for nearly all of the observations. The precision obtained for the calcium lines is considerably higher than for the remainder of the lines in the spectrum.

The list of photographs is given in Table I, together with the Greenwich Mean Time of the middle of each exposure and the phase based upon a period of 3.5225 days and referred to the epoch 1917, January 1.0. In view of the long interval covered by the observations the period is known with a considerable degree of accuracy. The results for the velocity, as derived from the hydrogen and helium lines on the one hand and the calcium lines on the other, are combined into mean values for plates taken near the same phase. These normal values, together with the mean phases, are given in Table I, the number of plates being indicated by the figures in parentheses. It was not possible to measure the calcium lines upon all of the negatives, since they occur near the end of the spectral region photographed, and a dense negative is required for the purpose. For this reason the mean phase and the number of plates differ in several cases for the hydrogen and the calcium results.

¹ Contributions from the Mount Wilson Solar Observatory, No. 149.

TABLE I

PLATE No.	DATE	G.M.T.	PHASE	MEAN PHASE		MEAN VELOCITY		O—C		REMARKS
				H and He	Ca	H and He	Ca	H and He	Ca	
4849	1916, May 20	23 ^h 42 ^m	0 ^d 424	0 ^d 408 (2)	0 ^d 392 (1)	—241	—34	+ 0.8	—1.6	
5514	1917, Feb. 5	14 48	0.392							
5384	1917, Jan. 1	15 51	0.660							
6278	1917, Oct. 6	21 42	0.627	0.678 (4)	0.672 (3)	—251	—32	—10.6	+2.8	
6279	1917, Oct. 6	22 23	0.656							
6329	1917, Oct. 31	15 05	0.70							
5287	1916, Dec. 4	17 15	0.899							
6376	1917, Nov. 25	14 51	1.03	1.010 (4)	1.010 (4)	—173	—37	+ 9.8	—3.0	
6377	1917, Nov. 25	15 19	1.05							
6378	1917, Nov. 25	15 48	1.06							
4854	1916, May 21	23 27	1.417							
5472	1917, Jan. 30	15 04	1.448							
6229	1917, Sept. 30	16 41	1.463	1.434 (5)	1.426 (3)	—25	—24	+ 0.1	+5.0	
6230	1917, Sept. 30	17 00	1.476							
6281	1917, Oct. 7	15 28	1.367							
4305	1915, Aug. 18	0 00	1.718							
6237	1917, Sept. 30	21 51	1.678	1.699 (3)	1.699 (3)	+ 81	—24	—7.7	—3.1	
6238	1917, Sept. 30	22 23	1.700							
6201	1917, Oct. 25	18 22	1.88	1.885 (2)	1.885 (2)	+140	—26	—10.9	—8.1	Process Plate
6202	1917, Oct. 25	18 42	1.89							
4916	1916, July 10	23 13	2.092							
5401	1917, Jan. 13	14 47	2.050							
5402	1917, Jan. 13	15 52	2.094	2.057 (5)	2.072 (3)	+194	—18	+10.8	—1.7	
6206	1917, Oct. 25	21 45	2.02							
6207	1917, Oct. 25	22 02	2.103							
5016	1916, Aug. 18	20 51	2.247	2.246 (2)	2.246 (2)	+189		+ 3.1		40" Camera
5029	1916, Sept. 9	0 03	2.245							
3959	1914, Dec. 25	16 10	2.399							
5018	1916, Aug. 18	23 40	2.364	2.382 (2)	2.399 (1)	+153	—13	—15.3	+2.5	40" Camera
4922	1916, July 11	23 16	3.094	3.164 (2)	3.094 (1)	—80	—14	—2.4	+2.0	Seed 23 Plate
5034	1916, Sept. 9	23 48	3.233							
5338	1916, Dec. 10	18 03	3.410							
5452	1917, Jan. 11	15 09	3.586							
5493	1917, Feb. 1	15 25	3.462	3.486 (3)	3.486 (3)	—164	—27	+10.1	—3.2	40" Camera

Except as noted in the table a dispersion of one prism and a camera of 18 inches (45.7 cm) were used in the spectrograph. The plates with but two exceptions were Seed Gilt Edge 27. With this combination the exposure times averaged from 15 to 25 minutes. This relatively short exposure is advantageous in view of the very rapid change of velocity in some portions of the velocity-curve.

The lines measured upon the photographs and the wave-lengths employed are as follows:

Ca.....	3933.825	He.....	4388.100
Ca.....	3968.625	He.....	4471.646
He.....	4026.342	Mg.....	4481.400
H.....	4101.900	Fe.....	4549.642
He.....	4143.919	H β	4861.527
H γ	4340.634	He.....	4922.096

The spectrum of the iron arc was used for comparison purposes on all of the spectrograms.

THE ORBIT AS DERIVED FROM THE HYDROGEN AND HELIUM LINES

The well-known graphical method of Lehmann-Filhés was used for the derivation of the approximate elements of the system. These elements were then corrected by means of differential formulae, a least-squares solution being used and the eleven normal values of Table I being assigned weights according to the number of plates involved. A convenient summary of the formulae to be employed is given by Plummer in his article on the determination of the orbits of spectroscopic binaries.¹ The resulting definitive elements are as follows, the letters having their usual significance. The errors given are probable errors.

$$U = 3.5225 \text{ days (assumed)}$$

$$K = 217.4 \pm 3.4 \text{ km}$$

$$\omega = 323.0 \pm 10.2$$

$$e = 0.094 \pm 0.020$$

$$T = 1917, \text{ January } 2.865 \pm 0.098 \text{ G.M.T.}$$

$$\gamma = -44.9 \pm 5.5 \text{ km}$$

$$a \sin i = 10,480,000 \text{ km}$$

$$\frac{m_1^3}{(m+m_1)^2} \sin^3 i = 3.71 \text{ sun's mass}$$

¹ *Astrophysical Journal*, 28, 212, 1908.

The differences between the observed values of the radial velocity and those computed from these elements are given under O-C in Table I. The average deviation is 7.4 km. A graphical representation of the velocity-curve and of the observed velocities is given in Fig. 1.

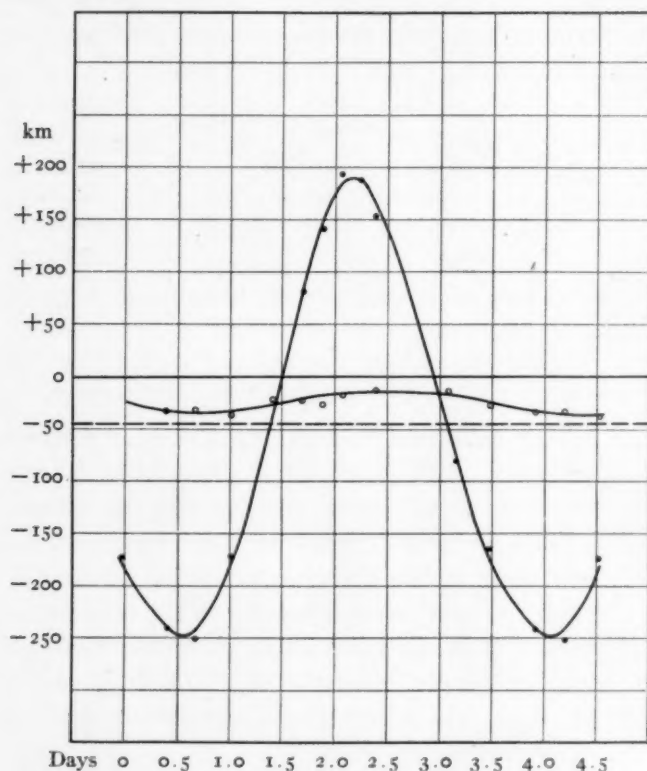


FIG. 1

The most convenient form for the calculation of the radial velocity at any phase of the period, and hence for the comparison of future observations with these results, is by means of a Fourier's series connecting velocity with phase. If we put $\tau = \frac{2\pi}{U}(t - t_0)$ we may represent the velocity V by the equation

$$V = a_0 + a_1 \cos \tau + a_2 \cos 2\tau + \dots \\ + b_1 \sin \tau + b_2 \sin 2\tau + \dots$$

The epoch t_0 has been taken as 1917, January 1.0. The coefficients in this series have been determined in the usual way with the following result:

$$V = -49.3 - 145.3 \cos \tau + 18.2 \cos 2\tau + 10.0 \cos 3\tau - 5.2 \cos 4\tau \\ - 147.0 \sin \tau + 18.2 \sin 2\tau - 7.3 \sin 3\tau + 6.1 \sin 4\tau$$

The agreement of the radial velocities computed from this formula with those observed is considerably better than that of the velocities calculated from the elements, the average deviation being 3.0 km instead of 7.4. This result is due to the use of nine constants as compared with the five constants of the orbit.

THE CALCIUM LINES

An examination of the radial velocities obtained from the calcium lines seems to give distinct evidence of a small variation with the same period as that for the hydrogen lines within the limits of error of the observations. If we apply to these results the method of representation by a Fourier series, we obtain the following equation:

$$V = -23.5 - 1.88 \cos \tau + 1.29 \cos 2\tau - 0.58 \cos 3\tau \\ - 10.41 \sin \tau - 0.94 \sin 2\tau - 0.42 \sin 3\tau$$

The velocities calculated from this formula when compared with the observed values give the residuals shown in Table I. The average deviation is 3.3 km. The velocity-curve for the calcium lines is shown in Fig. 1, the observations being represented by small circles. The motion of the system is -23.5 km.

THE SPECTRUM OF THE SECOND COMPONENT

Several of the photographs show evidences of the presence of the second component of the system, and on a very few plates we have been able to secure measurements of velocity. They are, however, too few in number to be used in the calculation of the orbit. The secondary spectrum appears to be of nearly the same type as the primary, and the lines are seen most clearly when the principal star shows its maximum positive velocity.

DISCUSSION OF THE RESULTS

The principal features of interest in connection with these results are as follows:

1. The variation of velocity shown by the hydrogen and helium lines is remarkably large, amounting to nearly 450 km.
2. The calcium lines indicate a variation in velocity of about 20 km with the same period as that shown by the hydrogen and helium lines.
3. The motion of the system as derived from the two sets of lines differs by about 20 km.

It is evident that the variation of velocity indicated by the calcium lines favors the view that the calcium gas producing these lines is connected with the binary system and is not a detached cloud in space. This is in accordance with the observations of Jordan,¹ Lee,² and others on spectroscopic binaries of similar character. On the other hand, the difference in the motion of the system as derived from the hydrogen and the calcium lines would seem to indicate an independent source of origin for the latter in accordance with the original suggestion of Hartmann.³ It seems to us probable that the calcium gas is actually connected with the stellar system, and that the difference in the apparent motion of the system is not to be interpreted wholly on the basis of velocity. A systematic displacement of the calcium lines relative to the other lines in the spectrum might readily come about from a marked difference in the distribution of the gases around the stars. Whether it could amount to as much as 20 km is, however, doubtful. A very probable source of difference may be the presence of the spectrum of the secondary component. As we have already stated, this is seen most clearly at the time of maximum positive velocity of the principal component. At other times it would blend with the stronger spectrum and thus introduce a possible source of systematic error into the measured displacements.

An important result which may have a direct bearing upon this question was obtained by Beal at the Allegheny Observatory in

¹ *Publications of the Allegheny Observatory*, **2**, 63, 1910.

² *Astrophysical Journal*, **37**, 1, 1913.

³ *Astrophysical Journal*, **19**, 268, 1904.

1915.¹ A series of observations upon the spectroscopic binary η Orionis, which belongs to the class with abnormal calcium lines, showed that the motion of the system had undergone a change of 25 km in the interval between 1902 and 1915. Whether this result is interpreted as the effect of the presence of a third body, or as a change due to variations in the physical and mechanical conditions in the system, it is clear that a factor is introduced which may go far toward explaining the results found in the case of Boss 46.

MOUNT WILSON SOLAR OBSERVATORY
March 1918

¹ *Report of the Eighteenth Meeting of the American Astronomical Society.*

REVIEWS

Table of $\log_{10} \sec^2 \theta$ for Determining Photographic Densities by Means of Nicol Prisms. Computed by PAUL S. HELMICK. University of Iowa Monographs, No. 4. Iowa City: The University, 1917. Pp. 14.

This table is intended for the use of those desiring to measure photographic densities with apparatus employing nicol prisms in its construction. The table gives the photographic density of the plate, i.e.,

$$\log_{10} \frac{\text{Incident light}}{\text{Transmitted light}}$$

directly in terms of the angle of rotation of the nicols. The value of the function is given for every 0.5° from 0° to 98° and for every 0.01° from 89° to 90° , together with tabular differences.

The table may be obtained free by addressing the Librarian of the State University, Iowa City, Iowa.

This table will doubtless be found useful for workers in this field, although a reviewer can easily find points of criticism. The table could be issued in a more compact form, and the densities rounded off to 0.001, as the third decimal is quite uncertain in actual measures of photographs. Certain improvements in the typographical appearance could be suggested, but will not be necessary for persons making regular use of the table.

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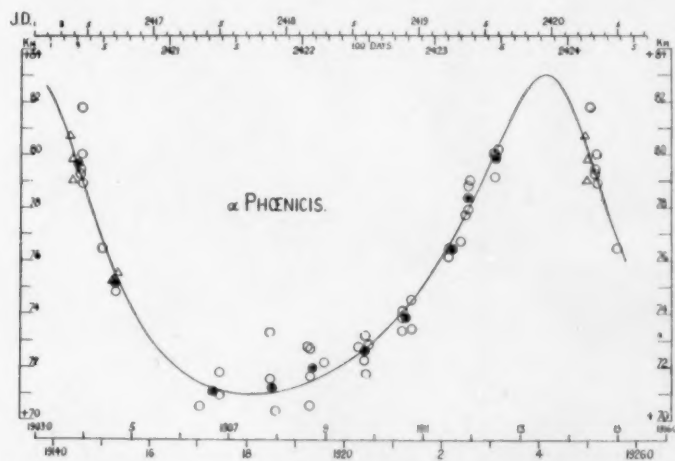
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Velocity-curve of the spectroscopic binary α Phoenicis

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ANNOUNCING
THE SUMMER QUARTER 1918
AT
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THE war has emphasized as never before the need of the nation for highly skilled men and women, and an obvious obligation rests on every citizen speedily to develop the greatest possible capacity for service.

The Summer Quarter of the University of Chicago affords an unusual opportunity to hasten the completion of any general training already begun, and to secure special intensive training in lines immediately related to war needs, e.g., ordnance supply, military science, food conservation, first aid, spoken French, etc.

In 1918 the Summer Quarter will begin June 17 and close August 30. The First Term will begin June 17; the Second Term, July 25. Students may register for either Term or for both. Students entering at the beginning of the Second Term may register for courses for which they have had the prerequisites. The courses during the Summer Quarter are the same in character, method, and credit value as in other quarters of the year.

A large proportion of the regular Faculty of the University, which numbers over three hundred, and also many instructors from other institutions, offer courses in the Summer Quarter, and in this way many varied points of view are given to students in their chosen fields of study.

ARTS, LITERATURE, AND SCIENCE

The University offers during this Quarter, in the Schools of Art, Literature, and Science, both graduate and undergraduate courses in Philosophy, Psychology, and Education; Political Economy, Political

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Science, History, Sociology and Anthropology, and Household Administration; Semitics and Biblical Greek; Comparative Religion; History of Art, Sanskrit, Greek, and Latin; Modern Languages; Public Speaking; Mathematics, Astronomy, Physics, and Chemistry; Geology and Geography; Botany, Zoölogy, Physiology, Physiological Chemistry and Pharmacology, Anatomy, Pathology, Hygiene and Bacteriology; and Military Science.

Divinity

The Divinity School is open to students of all denominations, and the instruction is intended for ministers, missionaries, theological students, Christian teachers, and others intending to take up some kind of religious work. The English Theological Seminary, which is intended for those without college degrees, is in session only during the Summer Quarter. The Graduate Divinity School is designed for college graduates. Pastors, theological teachers, students in other seminaries, candidates for the ministry, and other Christian workers, with requisite training, are admitted in the Summer Quarter.

The Chicago Theological Seminary will also be in session during the Summer Quarter, and its courses are open on the same conditions as those that obtain in the Divinity School.

Law

In the work of the Law School the method of instruction employed—the study and discussion of cases—is designed to give an effective knowledge of legal principles, and to develop the power of independent legal reasoning. The three-year course of study offered constitutes a thorough preparation for the practice of law in any English-speaking jurisdiction. By means of the quarter system students may be graduated in two and one-fourth calendar years. Regular courses of instruction counting toward a degree are continued through the Summer Quarter. The courses are so arranged that students may take one, two, or three quarters in succession in the summer only before continuing in the following Autumn Quarter. The summer work offers particular advantages to teachers, to students who wish to do extra work, and to practitioners who desire to study special subjects.

Medicine

Courses in Medicine constituting the first two years of the four-year course in medicine in Rush Medical College are given at the University of Chicago. For the majority of students taking up medical work for the

THE UNIVERSITY OF CHICAGO

first time, it is of decided advantage to enter with the Spring or Autumn Quarter. For the student who is lacking in any of the admission courses, or who seeks advanced standing, it is of especial advantage to enter for the Summer Quarter. All the courses offered are open to practitioners of medicine, who may matriculate as unclassified or as graduate students. Practitioners taking this work may attend the clinics at Rush Medical College without charge.

Education

In the Professional Schools the Graduate Department of Education in the School of Education gives advanced courses in Principles and Theory of Education, Educational Psychology, the Psychology of Retarded and Subnormal Children, History of Education, and Social and Administrative Aspects of Education. The College of Education is a regular college of the University, with all University privileges, and in addition provides professional training for kindergarten-primary, elementary- and secondary-school teachers and supervisors, and for special teachers in Home Economics and in Aesthetic and Industrial Education. It offers undergraduate courses in professional subjects and in the methods of arranging and presenting the various subject-matters which are taken up in the elementary and secondary schools.

Commerce and Administration

The School of Commerce and Administration is an undergraduate-graduate professional school, offering courses arranged to meet the needs of those preparing for various business pursuits, for commercial teaching, for secretarial work, and for philanthropic service. The work for the summer of 1918 will be organized, in co-operation with the School of Education, with especial reference to the needs of commercial teachers. In all the curricula emphasis is placed upon (1) broad foundations of work in history, political economy, sociology, psychology, biology, government and law; (2) an individualized curriculum; (3) contact with practical affairs; and (4) a professional spirit.

A series of public lectures in Literature, History, Sociology, Science, Art, Music, etc., scheduled at late afternoon and evening hours throughout the Summer Quarter, affords an opportunity to students and other members of the University community to hear speakers of authority and distinction in many departments of study and activity. This program will include a number of popular readings and recitals, open-air performances, concerts, and excursions to places and institutions of interest in and near Chicago.

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